The Indiana University Pervasive Technology Institute at 20: Two decades of success and counting

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PERVASIVE TECHNOLOGY INSTITUTE
INDIANA UNIVERSITY

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1. Executive Summary

In 1997, Myles Brand, Indiana University's 14th President, challenged the university to become "a leader [in higher education], in absolute terms, in the use and application of information technology." The Indiana University Pervasive Technology Institute (IU PTI) has been one of IU's most significant responses to President Brand's challenge. In its first 20 years, IU PTI's accomplishments have strengthened IU, the state of Indiana, and the nation. This report captures these accomplishments.

IU PTI's mission is to ***transform*** *innovations in cyberinfrastructure, computer science, informatics, and information technology into robust tools enabling new breakthroughs in research, scholarship, and artistic creation;* ***deliver*** *such tools and support their use in academic and private sector contexts;* ***aid*** *economic growth in the state of Indiana; and* ***strengthen*** *Indiana's 21st century workforce.* IU PTI acts locally, regionally, and nationally through its leadership, resources, and services, aligning with its motto: ***Accelerating innovation through advanced computing.***

IU PTI has evolved into a large and vital collaborative organization through its pursuit of six objectives:

1) **Creation and dissemination of knowledge:** IU PTI has contributed directly to 1,301 peer-reviewed scientific publications, a tally that excludes the many publications enabled by IU PTI innovations. IU PTI is similarly committed to broad dissemination of scientific knowledge broadly and organizes funding for Science Node, a free publication with over 140,000 readers.
2) **Development and deployment of advanced computing infrastructure:**
   a. IU PTI has transformed technology innovations from proofs-of-concept to widely used R&D tools in academia and research, and has created 72 such major services (hardware, software, consulting services) to accelerate discovery within the broad research community.
   b. IU PTI has created and deployed new software tools, releasing 73 open source software packages.
3) **Commercialization of Indiana University-developed technology**: IU PTI has cultivated a total of 11 startup companies, with four of these continuing today as significant business successes.
4) **Economic growth of Indiana:** IU PTI has enhanced the growth of Indiana's economy. Grant awards to IU PTI supported 862 person-years of full-time employment within IU, and, according to standard economic metrics, an estimated 2,100 job-years within Indiana.
5) **STEM workforce development:** IU PTI has stimulated interest in STEM fields through outreach events ranging from robot programming camps to displays at national and international conferences.
6) **Stimulation of IU's innovation pipeline**: IU PTI has stimulated IU's innovation pipeline by fostering new centers and areas of excellence. IU PTI has grown from three to a total of seven centers, with two labs created being incubated toward center status.

IU PTI's successes encompass four broad themes: creating knowledge, creating tools, developing people, and enhancing the economy. These successes have been supported by extramural funding, including $123,624,974 in public grant awards and $12,702,779 in private funding, for a total of over $136 million dollars to IU.

IU PTI's researchers exert national and international influence by sitting on advisory boards for federal funding agencies, founding research community organizations, and producing internationally distinguished scholarship while also responding to needs expressed by IU researchers. IU PTI influences university, state, and national priorities by pointing out new research directions gleaned from the insight, technical expertise, and imagination of its leaders and researchers.

The research landscape evolves continuously as new research tools, and new research needs, emerge. The COVID-19 pandemic has illuminated the utility of computational simulations to many new researchers, and they have illuminated new and exciting needs. These and many other challenges ensure that IU PTI will persist for another 20 years of *accelerating innovation through advanced computing.*

2. Introduction

In 1997, Myles Brand, Indiana University's 14th President, challenged the university to become "a leader [among institutions of higher education], in absolute terms, in the use and application of information technology."[1] The Indiana University Pervasive Technology Institute (IU PTI), initially called the Pervasive Technology Labs (PTL), was founded in 1999 to help IU achieve this goal. PTL was initiated through a $30M grant from the Lilly Endowment to IU in 1999, called "The Indiana Pervasive Computing RESearch Initiative – IPCRES."[2] The official start date of that grant award was September 22, 1999. Of that initial $30M, half went to fund the startup of PTL, and half to fund growth of the then-nascent IU School of Informatics (now the Luddy School of Informatics, Computing, and Engineering). Second-round funding of $15M in 2008 led to IU PTI's current structure. At the time of the 2008 award, President Michael A. McRobbie praised IU PTI's inception, noting that "creating the Pervasive Technology Institute is the logical next step to securing our position of leadership in the information technology field and will serve as a catalyst to our efforts to expand all of our research enterprises within the university and state." A timeline of IU PTI's critical accomplishments is provided in Appendix 1: IU PTI Timeline and Background.

IU PTI excels in research in computing, and in supporting computing resources for research, scholarship, and the arts. Collectively, the range of hardware, software, and human resources within the purview of IU PTI's expertise is now commonly referred to as "cyberinfrastructure"—a word popularized but never fully explained by the National Science Foundation. IU PTI created the now standard definition: "Cyberinfrastructure consists of computing systems, data storage systems, advanced instruments and data repositories, visualization environments, and people, all linked together by software and high-performance networks to improve research productivity and enable breakthroughs not otherwise possible."[3] IU PTI's mission, within and beyond Indiana University, is to create cyberinfrastructure, and to enable innovation through cyberinfrastructure.

An inherently collaborative organization, IU PTI draws talent from across traditional disciplinary boundaries and pools it within the generative environments of its centers. In essence, IU PTI was created to enable IU to respond to its own needs, and to those of the state and nation, more rapidly than might otherwise be possible within traditional academic structures. IU PTI has done that by working with the Luddy School of Informatics, Computing, and Engineering, the Maurer School of Law, the Kelly School of Business, and the College of Arts and Sciences. Collaboration with IU PTI has aided all of those academic units, but particularly so the Luddy School. Luddy has, in its history, been the academic responsibility center at the helm of three grant awards in excess of $10M (FutureGrid, Jetstream, and Jetstream2 advanced distributed/cloud computing systems). These three systems were all led by PTI-affiliated Principal Investigators, and these three together represent three out of a total of just 15 federal grant awards to IU Bloomington for research projects in excess of $10M. (A fourth grant proposal in excess of $10M was led by OVPIT but not affiliated with IU PTI). Such large projects are important

[1] Dunn, J. Michael, & McRobbie, Michael. (1998). *Information technology strategic plan: Architecture for the 21st century.* Indiana University. http://hdl.handle.net/2022/471

[2] The primary authors of the initial grant proposal were Michael A. McRobbie, Karen Adams, Director, Communications and Planning, Office of the Vice President for Information Technology, Dennis Gannon, then Professor of Computer Science at IU, and Gerald Bernbom, then special assistant to Vice President McRobbie. Gustav Meglicki, Technical advisor to VP McRobbie, and Craig Stewart, then Acting Director, Research and Academic Computing, played peripheral roles in the proposal preparation.

[3] NSF Advisory Committee for Cyberinfrastructure Task Force on Campus Bridging. *Final Report*. March 2011. Available from: https://vdocuments.us/download/national-science-foundation-advisory-committee-for-cyberinfrastructuretask-force-on-campus-bridging-final-report-march-2011 cites Stewart, C.A., S. Simms, B. Plale, M. Link, D. Hancock and G. Fox. What is Cyberinfrastructure? In: Proceedings of SIGUCCS 2010. Norfolk, VA, 24-27 Oct, 2010 in its definitional work around the word "cyberinfrastructure."

because of their scope and national impact. At the university level, IU PTI has played an important role supporting two of IU's "Grand Challenge" projects: the "Precision Health Initiative" and the "Prepared for Environmental Change" initiative. Perhaps the most striking example of IU PTI's ability to respond quickly and with talent amassed across internal boundaries within the academic structure of IU has been its involvement in national and international responses to the COVID-19 pandemic. At a time of international crisis, IU PTI proved ready and able to aid the nation.

Through its affiliation with the Research Technologies (RT) Division of University Information Technology Services (UITS), IU PTI offers significant computational, storage, and visualization cyberinfrastructure resources, as well as services that do not readily fall under the umbrella of supercomputing. IU PTI is a peerless organization; there is no other organization quite like it.[4]

The purpose of this document is to summarize IU PTI's accomplishments over the first twenty years of its existence and describe its current activities. Audiences for this document include:

- the Indiana University community, particularly so that this community can leverage IU PTI's personnel and capabilities;
- lawmakers, business leaders, and the public within the state of Indiana;
- leaders in the private sector, particularly leaders of IT firms nationally, and manufacturing and IT firms with a strong presence in the state of Indiana, so that they can take advantage of collaborations with IU PTI and understand the value IU PTI adds to the state's economy;
- members of the national scientific community, and program officers at federal funding agencies, so that they become more aware of the breadth and impact of IU PTI's activity;
- undergraduate students, so that they consider and enroll at Indiana University for graduate study;
- highly-skilled IT and cyberinfrastructure professionals, so that they consider Indiana University as a potential employer.

The document includes the following sections:

- *Section 3. IU PTI structure and function: A collaborative, interdisciplinary organization*. The section describes the mission, context, and functions of IU PTI.
- *Section 4. Metrics of IU PTI's success at IU and beyond*. This section includes tallies of IU PTI's most important metrics of success for its first 20 years (September 22,1999-September 22, 2019).
- *Section 5. Outcomes of IU PTI Activities (2015-2020).* This section offers key exemplars of IU PTI's activities demonstrating the importance and impact of its six major areas of functioning, focusing on major activities since the last comprehensive report of PTI activities.[5]
- *Section 6. Highlights of our 21st year.* This section includes many of the exciting items that emerged as we wrapped up out 20th year, including the Jetstream2 system and IU PTI's role in understanding and fighting the COVID-19 pandemic.
- *Sections 7 & 8 Centers and their accomplishments, and activities in IU PTI's 21st year*. These sections present narratives of each center's research program IU PTI's first 20 years, and highlights its 21st year.
- *Section 9. Conclusions and a look forward.*
- *Acknowledgments and appendices.* This report is intended to be largely "self-documenting" so in addition to the usual acknowledgments at the end of a report there are a number of informational and explanatory appendices.

[4] Please see Appendix 3 for a comparison of IU PTI and its closest analogs within the U.S.
[5] Please see McRobbie, Michael A. *Final Report to the Lilly Endowment, Inc.* Indiana University Pervasive Technology Institute. (2014). Available from: http://hdl.handle.net/2022/19787.

3. IU PTI structure and function: A collaborative, interdisciplinary organization

> *The mission of the Indiana University Pervasive Technology Institute (IU PTI) is to transform new innovations in cyberinfrastructure, computer science, and information technology into robust tools enabling breakthroughs in research, scholarship, and artistic creation; deliver such tools and support their use at academic institutions and in the private sector; accelerate the growth of the Indiana economy; and help build Indiana's 21st century workforce.*

The word "pervasive" in the name Indiana University Pervasive Technology Institute reflects the foundational importance of computer science, informatics, cyberinfrastructure, and information technology research to academic and industrial activities today. IU PTI's mission is a bit of a mouthful - essential to express its diverse local, regional and national roles. To express the essence of IU PTI's activities efficiently, it has also adopted the following motto: *Accelerating innovation through advanced computing*.

IU PTI's distinctive structure was designed to enable its persistence over time while it remains responsive to the needs of various communities. IU PTI consists of a core, with support and organizing functions, and a set of affiliated centers. Each center is, in turn, a collaborative organization involving participants from multiple disciplines. The solutions to many important problems often require collaboration across academic disciplinary boundaries. Within Indiana University, IU PTI enables such collaboration, fostering rapid responses to the needs of academia, society, industry, and business.

IU PTI is led by an Executive Director. Each of the directors of IU PTI-affiliated centers have the title of Associate Director, indicating their role in IU PTI's leadership and governance. Center directors may also, at their discretion, appoint leaders within their centers with the title of Assistant Director, IU PTI.

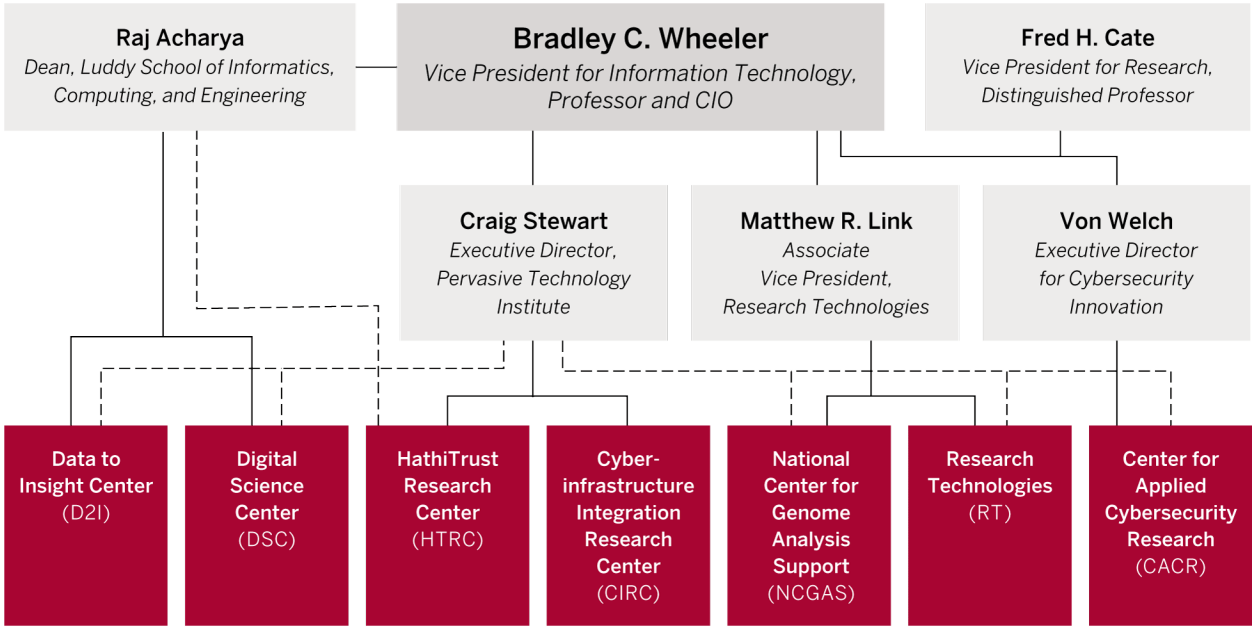

Figure 1. **Organizational structure of PTI as of September 2019.**

IU PTI's unusual positioning within Indiana University's overall organization is critical to its success. IU PTI reports to the Office of the Vice President for Information Technology (OVPIT), where it originated

as an effort led by then-VP Michael A. McRobbie. IU PTI is, however, a collaboration across many administrative and academic boundaries within IU, and enjoys partnerships with the following units:

- **Luddy School of Informatics, Computing, and Engineering** provides the primary affiliation for three of the current IU PTI centers, and supports IU PTI through salary, support for faculty members, space, and F&A return agreements for Luddy-led centers.
- **Maurer School of Law** has had strong ties with CACR since its inception in 2001 under its founding Director, Professor of Law Fred Cate.
- **Kelley School of Business** has strong ties with CACR and also plays an important role in many research projects across IU PTI having to do with economic development and systems analysis.
- **The College of Arts and Sciences** is home to faculty leaders involved in NCGAS, and to a large group of faculty collaborators who work with IU PTI to define challenging problems, help develop solutions, and then put those solutions to work creating new discoveries.
- **IU Libraries** has had strong ties with the HathiTrust Research Center.

IU PTI was designed to be able to react quickly to important university, state, and national needs through its capabilities to collaborate and work across organizational boundaries within IU. IU PTI is an organization that spans five major subunits of IU through collaboration and partnership is IU PTI operates on the philosophy that credit, unlike matter and energy, is a non-conserved property. One does not have less of it as a result of sharing it. This approach fosters a highly collaborative atmosphere—a foundational element of IU PTI's success. This philosophy breeds collaboration among centers with highly diverse foci, and fosters partnerships within the Indiana University, state, national, and international research communities. IU PTI, as an organization, is intended to persist over time while individual centers are expected to form, stay active for a period, and disband when they no longer provide practical benefit to the university or nation.[6]

3.1. PTI's major objectives

IU PTI pursues the following six major objectives:

1) **IU PTI creates and disseminates knowledge.**
   a. IU PTI creates knowledge, invents technology, and engages in research and development
   b. IU PTI supports the creation of knowledge, invention of technology, research, scholarship, and creativity.
   c. IU PTI disseminates knowledge through support for conferences and meetings in the sciences, humanities, and arts[7] and support for the online publication *Science Node.*

2) **IU PTI develops and deploys advanced computing infrastructure.**
   a. IU PTI transforms technology innovations from proofs-of-concept to widely used R&D tools in academia and research, bridging the gap between computer science and informatics research and products usable by IU and national research, humanities, and artistic communities. This competence is the source of much of IU PTI's funding success, as the institute is often tasked with developing services into production-quality software and/or hardware, and then delivering and supporting those services. This work benefits the Indiana University community in several ways, including the following:
      - Inventors of technology, tools, and services receive assistance transforming their inventions into the most useful and meaningful versions possible.

[6] Appendix 1 includes a list of centers formerly affiliated with PTI.
[7] One of Indiana University's Bicentennial Strategic Plan metrics includes the number of academic conferences held at Indiana University that bring scholars from other institutions to Indiana University. https://strategicplan.Indiana University.edu/plan/faculty.html#priority2

- The IU research, scholarly, and artistic communities benefit from earlier access to robustly usable versions of new innovations and services developed at IU than their peers and competitors at other institutions.

b. IU PTI creates and deploys new software tools, releasing most of these tools as "open source" software so that they may easily be adopted by the US national research community.

3) IU PTI leads and supports the commercialization of IU-developed technology.

a. When appropriate, IU PTI becomes directly involved in technology transfer to the private sector. This involves creating startup companies led by IU PTI-affiliated faculty and staff, and licensing innovations created by IU PTI.

4) IU PTI enhances the growth of Indiana's economy.

a. IU PTI aids Indiana's economic growth by consulting with and providing resources to private sector entities. Some services are provided at no cost (through collaboration) to entities in the state of Indiana, as part of IU's mission to enhance life in its home state.

b. IU PTI attracts talented, technically adept staff to Indiana, and keeps them happily employed within IU. Part of IU PTI's attractiveness as an employer is its collaborative nature and the importance of the challenges it pursues; it also enjoys a well-earned reputation for winning grants and contracts and for providing long-term funding for staff employed through such extramural funding. In addition to their intellectual contributions, these highly-skilled staff members contribute to Indiana's workforce and tax base – spending money from their salaries in Indiana – monies that originate primarily from federal funding agencies and which, in the absence of IU PTI, would likely go to a different state.

5) IU PTI aids the development of a strong STEM workforce in Indiana.

a. IU PTI aids the development of a strong 21st century Science, Technology, Engineering, and Mathematics (STEM) workforce in Indiana and the U.S., drawn as much as possible from native-born Hoosiers and others who adopt Indiana as their home. Though IU PTI does not offer any "for credit" courses within Indiana University, it arranges frequent non-credit training activities within the university, ranging from an hour to a few days in length. IU PTI also provides frequent outreach activities designed to interest young people in STEM careers, such as the annual "Robot Camp" offered each summer.[8]

6) IU PTI stimulates IU's innovation pipeline.

a. IU PTI fosters new centers and areas of excellence within Indiana University. IU PTI often serves an incubating function, helping new projects and initiatives grow into labs and, eventually, into full-fledged IU PTI centers.

b. IU PTI provides for the ongoing support and continuity of centers, sometimes through efforts such as routine delivery of support for grant writing, and sometimes by providing exceptional assistance to centers or labs that encounter periods of challenge in funding continuity.

3.2. IU PTI's role within IU and its research, development, and delivery agenda

IU PTI plays a critical role in Indiana University's overall strategy of leadership in information technology, computer science, advanced cyberinfrastructure, and high performance computing.

[8] UITS at Indiana University. (2015). *Ready, Set, Robots! Camp*. Available from https://www.youtube.com/watch?v=zWh9hWf0rBM&feature=youtu.be&list=PLqi-7yMgvZy8xB64_0-O7PId_uzTFy9PO

Just as a stool rests solidly on three legs, Indiana University's strategy in information technology, advanced computing, and cyberinfrastructure rests on three essential strengths:

1) Outstanding basic research in computer science, informatics, and engineering. These activities are led by Indiana University faculty, primarily from the Luddy School of Informatics, Computing, and Engineering, as well as the Maurer School of Law, the College of Arts and Sciences, the Kelley School of Business, and the Purdue School of Engineering and Technology at IUPUI.
2) Ground-breaking research, development, and delivery functions transforming innovations into significant tools, aiding research, scholarly, and artistic communities within and beyond Indiana University, bolstering Indiana's economy in the process. These activities are the focus of IU PTI.
3) Exceptional cyberinfrastructure, and staff supporting that infrastructure. These activities are led by the Research Technologies Division of University Information Technology Services, and by UITS generally, in activities beyond collaboration with IU PTI.

IU PTI enables a positive feedback loop in which the needs of Indiana University artists, scholars, clinicians, engineers, scientists, and researchers drive the IU PTI research agenda. IU PTI then transforms computer science, informatics, and cyberinfrastructure innovations into high-quality, robust tools usable by the Indiana University, national, and international research communities. IU PTI's research agenda is also influenced by U.S. federal funding priorities, and IU PTI, in turn, influences U.S. national research priorities through its actions and its colleagues' work. Due to proximity and collegial communication, IU PTI creates a competitive advantage for IU researchers in that innovations made here are used here first, before they are discovered by, and widely adopted at, other institutions. By supporting research interests in this way, IU PTI adds value to Indiana University, the state of Indiana, and the United States.

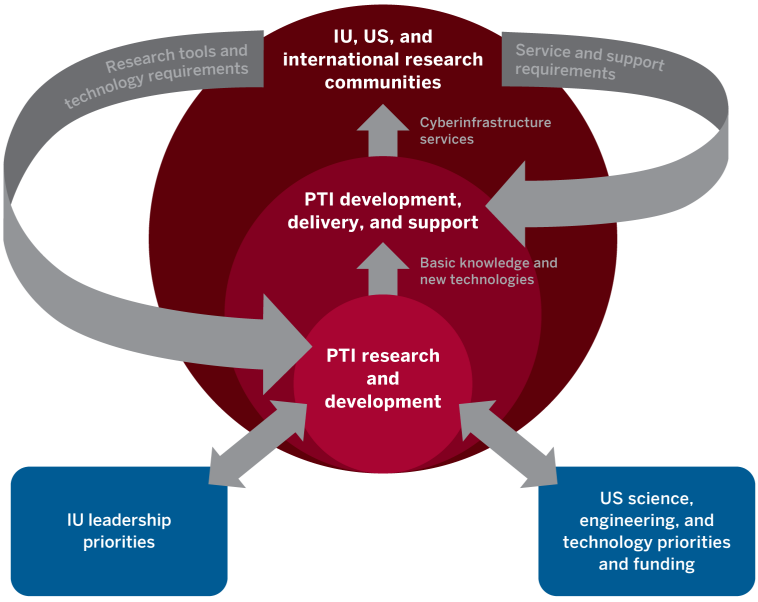

Figure 2. IU PTI's research and services activities: what drives IU PTI's activities, and how IU PTI drives Indiana University capabilities and national agendas.

This positive feedback loop that IU PTI creates is part of how IU PTI has developed over time. IU PTI works a virtuous, positive reinforcement cycle as depicted below:

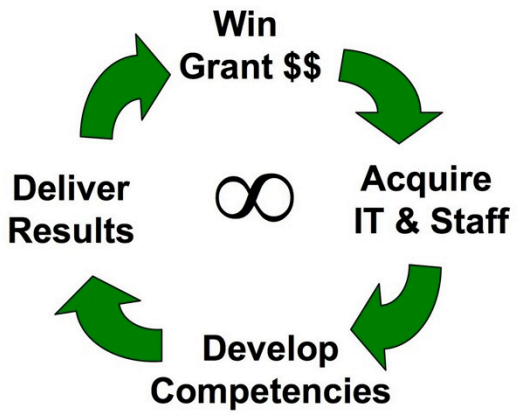

Figure 3. The virtuous cycle of competing for and winning extramural funding, developing competencies, delivering results that IU PTI has demonstrated over 120 years. Adapted from a figure created by former VP for IT Bradley C. Wheeler.

IU PTI's activities are made possible by external (so-called "extramural") funding. Less than 20% of IU PTI's budget comes from IU. The remaining 80% is primarily grant awards from federal research funding agencies, with smaller amounts from private charitable trusts, private companies, and grants and contracts with the state of Indiana. IU PTI pursues grant funding related to cyberinfrastructure when it aligns with IU's strategic goals, and when the following criteria are met:

- The work is of high value to funding agencies (federal and otherwise), and abides by policies. In other words, someone is willing to pay for it, and it is not classified.
- Indiana University has relevant faculty who can serve as intellectual leaders.
- Indiana University employs experts who can do the technical R&D work required.
- When IU PTI staff who are not tenured or tenure-track faculty lead grant proposals, they are not pursuing grants that compete with tenured or tenure-track faculty.[9]

One of IU PTI's most important functions involves shepherding the innovations developed via this virtuous cycle into widely-used tools. Each week, new academic papers and software releases herald the creation of a new prototype for a piece of software or cyberinfrastructure service. Most of these fulfill interesting and innovative functions, but few ever enjoy a useful life extending beyond the publication of an academic paper or perhaps the depositing of the prototype's code in a code repository. The difficult path from initial success as an idea to success as a widely-used product is often referred to as "the valley of death." Many ideas enter; few survive the climb up the other side. However, there are really two valleys of death: conversion of a new idea and new product from "proof of concept" into a tool used within research and development communities, and conversion from a widely used R&D tool to a consumer product. IU PTI plays an integral role in creating new technologies and guiding them from proof of concept into widely used R&D tool. IU PTI sometimes, but less commonly, helps commercialize new technologies. A longer discussion of the "two valleys of death" appears in Appendix 12.

[9] Some grants and contracts pursued and won by IU PTI involve situations in which a granting agency requires a level of control and commitment that exceeds what a tenured or tenure-track faculty member finds agreeable and consistent with the role of a faculty member. IU PTI's focus on proposals led by professional staff members or non-tenured academic appointees creates a competitive advantage for Indiana University when pursuing such funding relative to grants led by tenured faculty who seem likely to become an "absentee PI."

4. Metrics of IU PTI's success, at Indiana University and beyond

In the report to the Lilly Endowment summarizing IU PTI's accomplishments through its second round of funding,[10] Indiana University offered a highly-positive assessment of IU PTI's value and success. This section updates and expands on prior reports. Some of IU PTI's key metrics are summarized in Table 1, Table 2, and **Error! Reference source not found.** below. These metrics show the outcomes of 20 years of effort from September 22, 1999 through the end of September 2019. To give a sense of IU PTI's current activity levels, operating on an ongoing basis long after startup funding from the Lilly Endowment ended, totals for FY2019 (July 1, 2018-June 30, 2019 - the last full fiscal year before PTI's 20th anniversary) are included.

Table 1. Key metrics of accomplishment for IU PTI. These metrics include accomplishments of individuals, labs, and centers while they were formally affiliation with PTL or IU PTI. *These numbers are underestimated, as these statistics were not counted reliably prior to 2011.

Metric	Total from inception to end of September 2020	Appendix with detail or reference
1. IU PTI creates and disseminates knowledge.		
Projects leading to Nobel Prizes supported by IU PTI	3	
PTI Technical Publications	1506 total; 1301 peer-reviewed	https://bibbase.org/service/mendeley/42d295c0-0737-38d6-8b43-508cab6ea85d
Data sets published	177	http://hdl.handle.net/2022/25793
Other digital products (not counting open source software or presentations)	8	http://hdl.handle.net/2022/25793
Best Paper awards	11 Best Papers; 1 Best Student Paper; 3 Best Paper finalists	A3.1
Major National and International Group Awards	4 SCxy Challenge awards, 1 SCxy honorable mention (counting predecessors to PTI that were later involved in PTI), 1 SCxy Student Cluster Competition award, IUAnyWare, Campus Technology for Jetstream	A3.2
Conferences led / hosted	52	A3.3
2. IU PTI develops and deploys advanced computing infrastructure.		
PTI grant and contract total from federal sources	$123,624,974	
PTI grant and contract total from non-federal sources	$12,702,779	
Total grants and contracts for PTI	$136,327,753	

[10] McRobbie, M.A. (2014). *Final Report to Lilly Endowment Inc.* Indiana University Pervasive Technology Institute. https://scholarworks.Indiana University.edu/dspace/handle/2022/19787

Major services (e.g. visualization services, online computing tools, science gateways, major computing systems) offered	72	A3.4
Open source software titles created	73	A3.5
3. IU PTI leads and supports the commercialization of IU-developed technology.		
Patents awarded to PTI-affiliated staff or faculty	12	A3.6
Number of commercial licenses executed	5	A3.7
Startup companies created by someone affiliated with PTI	11	A3.8
4. IU PTI enhances the growth of Indiana's economy.		
Startup companies in which PTL and PTI made an investment as an Angel Investor	2	A3.9
Major collaborations with businesses operating in Indiana (including international businesses with a significant presence in Indiana)	9	A3.10
Major collaborations with international businesses that do not have a major presence in Indiana	3	A3.10
Person-years of employment created directly within PTI / Indiana University (actual grant headcount)	862.8 person years (Full Time Equivalents)	
Job-years of employment in the State of Indiana created as a side effect of PTI grant awards as estimated by the IMPLAN methodology	2100 job-years	
5. IU PTI aids the development of a strong STEM workforce in Indiana.		
Students receiving Ph.D. degree (who worked in or were supported by an IU PTI-affiliated center)	73	A311
Number of students who received a Ph.D. and went on to tenure-track faculty positions	22	A3.11
Total readership of Science Node (www.sciencenode,org), a free electronic publication about computing and science	143,866	
6. IU PTI stimulates IU's innovation pipeline.		
Total number of new centers created or newly brought into affiliation with PTI since organization into centers and labs in 2008	4	
Total number of new labs created or newly brought into affiliation with IU PTI since organization into centers and labs in 2008	2	

The details for most of the metrics listed in the table above are set out in this document's appendices. A list of IU PTI's technical publications is available online.[11] Counts for each publication type are presented below in Table 2. A detailed timeline of IU PTI's major accomplishments is also available online.[12]

Table 2. Technical publications by IU PTI-affiliated individuals from 1999-2019.

[11] https://bibbase.org/service/mendeley/42d295c0-0737-38d6-8b43-508cab6ea85d
[12] pti.iu.edu/about/timeline

Metric	Total fin IU PTI's first 20 years – to September 2020
Journal Articles, Peer Reviewed	503
Conference Proceedings, Peer Reviewed	740
Book Chapters	58
Subtotal peer-reviewed publications	*1301*
Technical reports (most self-published through IU ScholarWorks, IU's digital online repository)	205
Total technical publications	***1506***

To give a sense of IU PTI's scale and the evolution of its size over time, IU PTI's predecessor—the section of UITS focused on research computing—employed only 24 people the year before Michael A. McRobbie arrived as Indiana University's first VP for Information Technology and CIO. As of the end of FY2020 (30 June 2019), there were a total of 121 FTEs working in IU PTI-affiliated centers: 67 FTEs were funded with university monies (most of these in RT). Within IU PTI, a total of 54 FTEs were supported by external contracts and grants.

5. Outcomes of IU PTI Activities

The facts and figures in Table 2 present a highly positive picture of IU PTI's activities and accomplishments in research and development. But there is much more to IU PTI than just counts of publications and events and dollars of grant awards. Earlier reports have summarized the activities of the PTL up to 2007[13]and through the end of funding from the Lilly Endowment in 2014.[14] These reports are well worth reading; this report emphasizes activities since 2014, but begins with exemplars from the early years of PTI that proved fundamental to its long term success. Other key activities from the earlier years of existing PTI-affiliated centers, as well as summaries of the activities of labs and centers created by PTL and PTI that have been closed, are presented in section 7.2.

5.1. Early successes

5.1.1. Data-centric computing

Data-centric computing has been a focus area for IU PTI from almost the beginning, starting with the success of a project called Linked Environments for Atmospheric Discovery (LEAD). LEAD was a system for analyzing and predicting tornado paths. This project, led by University of Oklahoma Professor Kelvin Drogemeier (now Director of the White House Office of Science and Technology Policy), and involved PTL Science Director Dennis Gannon and Professor Beth Plale.

[13] McRobbie, M.A., Adams, K., Baker, M. P., Fox, G., Gannon, D., Heiland, R., Lumsdaine, A., McMullen, D., Miller, T., Siefert-Herron, D., Stewart, C., Wallace, S., Pierce, M., & Travis, G. *Pervasive Technology Labs Program Report 2007*. Report to the Lilly Endowment. (2007). Available from: http://hdl.handle.net/2022/3210.

[14] This report outlines the maturation of the IU Pervasive Technology Institute from the end of the name and structure of the "Pervasive Technology Labs" to the point that IU PTI was able to sustain itself with just a small amount of ongoing support from IU.

The LEAD project demonstrated the power of a data-centric approach to using supercomputers for solutions to real-world problems. This project was the starting point for three of IU PTI's current centers:

- The Data to Insight Center, led to this day by Professor Beth Plale, which focuses on new creation of data-centric scientific concepts and tools
- The Cyberinfrastructure Integration Research Center, led by Dr. Marlon Pierce, which has taken the concept of Science Gateways developed by Professors Plale and Gannon and created a whole suite of software tools and computational environments based on it
- The HathiTrust Research Center, a group focused on data-centric approaches to humanities scholarship, and itself sprung out of a data science project led by the Data to Insight Center

5.1.2. Concept-centered approaches to cybersecurity

CACR is one of the oldest IU PTI-affiliated centers; that affiliation, however, came well after the center was created. CACR was founded in 2001 by then-VP Michael A. McRobbie, with Law Professor Fred Cate as director. Consistent with Professor Cate's expertise, CACR in its early days focused on policy and privacy. Cate was very well known for his privacy work in particular and was frequently called upon to offer his expertise on such issues in Washington, D.C. Other cybersecurity centers have focused on technology first, assuming that the solutions to cybersecurity problems lie in technological approaches. CACR has always focused on principles and policies in the belief that security policy and privacy concerns should drive technological development. That approach – principles and policy first, technology following those principles – has enabled CACR to grow into one of the nation's most significant centers for cybersecurity policy and technology.

5.1.3. Creation of new cyberinfrastructure systems and resources

One of the most easily visible outcomes of collaboration between parts of IU that are now all affiliated with IU PTI is in IU's rise in the world of advanced computing systems. In 1997 Indiana University had its first display at the prestigious IEEE/ACM Supercomputing Conference (more explanation of this conference is in section 13.2 below). The university was not yet well known for advanced computing, and one of the questions commonly posed to representatives at display booth was, "Why does IU have a display at this conference?" No one asks that anymore. IU's climb to prominence was fueled by collaboration between RT and faculty of IU PTI, though there was no formal tie between RT and PTL prior to 2005. Key highlights in IU's rise to prominence in advanced computing include the following:

- *Supercomputers and high performance computing clusters.* RT services include designing and implementing supercomputers used by IU and the national research community, including:
    - The first university-owned 1 TeraFLOPS (trillion floating point operations per second) supercomputer in the US (2001). The IBM-manufactured "Research SP" was capable of one trillion mathematical operations per second. This system was one of the first IU systems to be made available to the US research computing community, as part of IU's engagement in TeraGrid (discussed on page 24). Led by the RT, this system's development benefitted from the involvement of PTL's initial Science Director, Dennis Gannon.
    - The AVIDD cluster (Analysis and Visualization of Instrument-Driven Data), which was the first distributed Linux cluster to achieve more than 1 TeraFLOPS on the LinPack benchmark program (2003). AVIDD was made possible by a grant award from the National Science Foundation to IU under the leadership of Principal Investigator Michael A. McRobbie, at that time VP for IT. Like the Research SP above, AVIDD was made available to the national research community as part of IU's involvement in TeraGrid. AVIDD was developed, implemented, and led by Craig Stewart with the deep involvement of IU PTI-affiliated faculty members Dennis Gannon and Beth Plale, as well as affiliated Computer Science faculty member Randy Bramley.

    - Big Red, IU's best-ranked supercomputer ever on the Top500 list, which lists the world's 500 fastest supercomputers. Unveiled in 2006, it was the original of the "Big Red" family. This 20.5 TeraFLOPS system debuted at position number 23 on the Top500 list. While IU has had many systems on many of these prestigious twice-a-year listings, no IU supercomputer has ever been higher on that list than the original Big Red. Big Red was also available to the national research community via TeraGrid, and was for a considerable amount of time the fastest systems part of TeraGrid in running the important molecular simulation program NAMD. Many breakthroughs in the understanding of cell function were made by researchers across the US running simulations with NAMD on Big Red. Big Red was developed under the leadership of Craig Stewart, who was COO of PTL and led RT at the time, in partnership with IU PTI-affiliated faculty member Andrew Lumsdaine.
    - Big Red II, the first university-owned 1 PetaFLOPS supercomputer in the US (2013). A PetaFLOPS is a quadrillion mathematical operations per second, equal to1000 TeraFLOPS. Big Red II was the beginning of the very successful partnership between Cray Inc., known as "America's supercomputer company," and IU. The architecture of Big Red II was developed primarily by RT leaders Matt Link and David Y. Hancock, with important input from IU PTI-affiliated leader Thomas Sterling
- *Advanced storage systems.* RT has also been a leader in advanced storage systems.
    - *Tape storage systems.* IU was one of the first universities to install a major tape storage system operated with the very secure High Performance Storage System (HPSS), in 1999. HPSS was designed for use at a classified US nuclear weapons lab. IU installed one tape library in Bloomington in 1999 and then, in 2001, installed a second tape library in Indianapolis. RT then wrote code enabling the two different tape storage systems to "mirror" each other; IU was the first university in the world to use this approach, ensuring that IU's research data was stored in duplicate, 50 miles apart. IU's official digital archive, IU ScholarWorks, depends on RT's tape storage system for its data storage. Like several of IU's storage systems, the Scholarly Data Archive (as this tape storage system is known) was made available for use by the US research community generally through TeraGrid. IU's tape storage systems were envisioned and funding was obtained by then-VP McRobbie.
    - *Disk-based systems.* IU leadership in disk-based storage systems began in 2005 with a grant award from the NSF to IU with Principal Investigator RT Associate Dean and IU PTI COO Craig A. Stewart in 2005. With this grant, IU built one of the fastest massive disk-based data storage systems in the US based on the high performance open source disk storage software Lustre. It was the fastest and most widely used disk storage systems ever connected to the TeraGrid. IU has operated one or more local storage systems based on the high performance Lustre system ever since. RT has also played a lead role in national and international leadership of the Lustre file system project, including two periods with IU storage expert Stephen Simms serving as the group's chairperson. IU PTI-affiliated faculty members Beth Plale and Denis Gannon were both involved in the conceptualization of this project.

5.1.4. High performance software tools

Supercomputers are only useful when they remain fast while running software. This requires more than just hardware; rather, it takes innovation and excellence in software implementation. High performance software systems have, like data-centric computing, been a hallmark of IU PTI since its inception. Key faculty members affiliated with IU PTI and working in this area have included Geoffrey C. Fox, Andrew Lumsdaine, Thomas Sterling, and D. Martin Swany.

One early example of high performance software from Fox's lab is the NaradaBrokering system. NaradaBrokering was a content distribution infrastructure for web-based applications and enabled the development of secure, failure-resilient web based systems. The concepts behind NaradaBrokering are still used today in Web-based distributed computing systems and in supercomputers.

Graph problems are a vast category of mathematical and computing problems. Everything from interconnectedness of web sites to the processing of "big data" can be expressed as a graph problem. IU PTI has been involved in developing software for graph processing and related high performance computing tools from its earliest days. Notable software developments include the following:

- The BOOST graph library was an early and important contribution to high performance computing software. Created under the leadership of Open Systems Lab/CREST Director Andrew Lumsdaine, the BOOST graph library was, for many years, one of the best performing and most widely used software tools for solving graph problems.
- HPX – High Performance Parallax – was a runtime system developed by former CREST Director Thomas Sterling, perhaps best known as the father of Beowulf computing clusters, and for designing the architecture used in the world's fastest supercomputers for more than a decade. HPX was a software system that inherently incorporated ideas from graph libraries.

Digital Science Center Director Geoffrey Fox has most recently been an international leader in the creation of software that integrates "big data" tools with high performance supercomputer tools. Additionally, several exciting contributions from IU PTI in the area of high performance computing have come from the innovations of Luddy School Professor D. Martin Swany, affiliated with D2I, who has developed performance tools to enhance software from wide area networks to individual supercomputers.

All in all, high performance software has been a focus of

- Digital Science Center (DSC)
- Center for Research in Extreme Scale Technologies (CREST)
- Research Technologies (RT)
- Data to Insight (D2I)

5.2. IU PTI accomplishments, with a focus on 2014-2020

5.2.1. IU PTI creates and disseminates knowledge.

IU PTI has created thousands of peer-reviewed scientific papers, technical reports, and data sets, and has supported many types of scholarly research. A few important examples of knowledge created and disseminated by IU PTI include the following:

- *Security from first principles.* All too often in the history of cybersecurity, experts have thought of the problem as being one of taking an existing system and securing it against bad actors. In the book *Security from First Principles*, CACR experts Craig Jackson, Scott Russell, and Susan Sons explain tools and techniques that allow software engineers to build software from the first comment line to finished code in ways that lead to inherently well-secured software. This concept is revolutionizing cybersecurity today.[15]
- *FAIR data.* FAIR refers to a critical concept in production of data and other digital assets expressing that they should be Findable, Accessible, Interoperable, and Reusable. IU PTI has advanced the development of specific tools that implement FAIR data policies. In Washington

[15] Jackson, C., Russell, S., & Sons, S. 2017. *Security from First Principles*. O'Reilly Media, Inc. ISBN: 9781491996904.

D.C., D2I director Beth Plale has spent the last three years leading the development of data policies and guidance for creating reusable data for the NSF; this work will impact open research in the US for years to come.

- *Big Data and High Performance Computing*. Money is being poured into "Big Data" style computing, yet often without incorporating well-known techniques of HPC computing. At the same time, HPC computing must incorporate new techniques developed in the Big Data world or risk falling into irrelevance. The Digital Science Center, led by Director Geoffrey C. Fox, has emerged as an intellectual leader in creating "knowledge maps" that link HPC and big data software, and in developing software and software libraries that integrate tools from HPC and Big Data approaches to large scale computing.
- *Return on Investment (ROI) analysis of advanced cyberinfrastructure.* It has been an article of faith at IU for more than half a century that IU's investments in cyberinfrastructure accelerate research and development. IU PTI has emerged as the national leader in the analysis of Return on Investment in advanced computing. These analyses show conclusively that IU's investment in on-premise facilities are highly cost effective. Systems such as the Big Red series of supercomputers enable analyses not easily performed in cloud systems, and at a cost much lower than would be paid for cloud systems. Similarly, the IU PTI Jetstream cloud system provides straightforward interactive computing tools at a price much lower than commercial cloud services.

Within these areas of expertise, IU PTI has both exerted influence on and been influenced by national research needs. Security from first principles and big data/high performance computing are areas in which IU has responded to clear research community needs. In the case of FAIR data, IU has helped define a need and influenced the federal government to identify this area as a need; it then one of the US institutions best positioned to help meet that need. IU PTI's involvement in ROI research was initially a result of a request for work on this specific topic from the US federal government that grew into another area of national leadership for IU PTI.

Producing new knowledge is important, but that knowledge must be transmitted and put to use in order to be meaningful. Scientific, technical, scholarly, and artistic conferences are a way to transmit information, build communities, and aid in the transformation of new inventions into practical tools. Tens of thousands of people have been made aware of IU and its capabilities as a result of IU PTI leadership at conferences. Hosting conferences is also a way to attract people to IU as faculty members, staff, and students. IU PTI has led and/or hosted a total of 47 conferences, serving constituencies from local to international. Three examples of such conferences include the following:

- *The I-Light Conference.* In the early 21st century, IU was at the forefront of networking research and development, and implementation of its own network. Indiana University and Purdue University received state funding to develop a high speed network that connected the Purdue West Lafayette, Indiana University Purdue University Indianapolis, and Indiana University Bloomington campuses, and connected them to the Internet2 national high speed network that travelled through Chicago. In 2002,[16] 2004,[17] and 2005,[18] IU and Purdue universities hosted a statewide "I-Light Conference" to share information about how best to use this network capability, and to describe research advances and accomplishments made possible by this network funded by a special state appropriation. Proceedings of this conference remain available

[16] G. Moore & C.A. Stewart. (eds.). (2002). *I-Light Applications Workshop 2002 Proceedings.* Indiana University. http://hdl.handle.net/2022/14002

[17] C.A. Stewart, G. Moore, & E. Wernert (eds.). (2004) *I-Light Symposium 2004 Proceedings.* Indiana University. http://hdl.handle.net/2022/13999

[18] E.A. Wernert, G.R. Bertoline, & G.S. Moore (eds). (2005). *I-Light: A Network for Collaboration Between Indiana University and Purdue University.* Indiana University. http://hdl.handle.net/2022/435

online and provide examples of just how far ahead of the rest of the nation Indiana was in its use of advanced networks.

- *PRAGMA 27*, hosted by the Data to Insight Center and IU Pervasive Technology Institute, October 15-17, 2014. PRAGMA is the Pacific Rim Applications and Grid Middleware Assembly, a major conference on grid computing and big data management. Beth Plale served as general chair and host bringing this distinguished international conference to IU Bloomington's CIB.
- *Galaxy Community Conference.*[19] Galaxy is one of the most important, and most widely used bioinformatics workflow tools in existence. Galaxy enables biologists to string together a set of different programs in order to analyze and understand the results of genetic and genomic research projects. Galaxy is specifically designed for ease of use by biologists and to make analyses easily replicable. The Galaxy Community Conference draws together hundreds of researchers each year to talk about their research with Galaxy, new tools they have developed for Galaxy, and new features they would like to have. IU PTI bid and won the right to host the GCC 2016 conference specifically with the idea that it would be a great way to bring many exciting biological research talks to IU and at the same time build excitement within the Galaxy user community about using the then brand new Jetstream cloud system. It worked. To this day Jetstream supports a larger percentage of allocations for biological research projects than any other system allocated through XSEDE.

Within Indiana University, IU PTI staff and affiliated faculty members collaborate with others within the university community, making new technologies available to IU before they are released to the larger US research community and described in academic publications. Some recent examples of IU PTI's role in supporting major research initiatives at IU include the following:

- *Indiana University Grand Challenge: Precision Health.* The IU Precision Health Grand Challenge Initiative is, quite simply, saving lives. Through this initiative, doctors have developed the most effective treatment in existence for "triple negative" breast cancer – a cancer that disproportionately affects Black women and which has a particularly poor prognosis. IU PTI's cyberinfrastructure and support enables advances in the many foci of the Precision Health Initiative Grand Challenges, including Cancer, Alzheimer's, and Diabetes, and has helped find new immunotherapeutic treatment for cancer and tools for diagnosing and understanding Alzheimer's. The largest US consortium studying Alzheimer's depends on IU's supercomputers and storage facilities as the core of its research enterprise.
- *Indiana University Grand Challenge: Prepared for Environmental Change.* The global environment is changing. One can argue about the causes and strategize about ways to decrease the impact of humans on the global environment, but we must also prepare for these changes as an imminent reality. Current predictions suggest that central Indiana may, in 50 years, have a climate similar to that of northern Texas. The Prepared for Environmental Change Grand Challenge focuses on education and information dissemination to decrease the impact of humans on the global environment. Research associated with the challenge also focuses on developing specific strategies that will prevent loss of species critical to ecosystem function in Indiana and the Midwest, and help humans in Indiana prepare for and adapt to changes in the environment that will affect all aspects of life.
- *HathiTrust Research Analytics.* IU PTI took on the role of leading the HathiTrust Research Center, a multi-state collaboration, and since then has made the copyrighted material of the Google Books project available to the nation as a production service, increased the total number of volumes available for analysis to 17 million, created new tools, and enabled critical new insights in humanities scholarship, particularly in studies of literature and history. HTRC is particularly proud to have played a role supporting the massive text search that has enabled

[19] Please see https://gcc16.sched.com and https://rna-seqblog.com/the-2016-galaxy-community-conference-gcc2016/

scholars to find, amplify, and reveal the voices of Black women who lived in the US in the 1800s. HathiTrust Research Analytics is a combination of software tools and a dedicated and highly specialized hardware platform. This center, and its national services, emerged from what was initially a research idea within D2I.

- *3-D digitization and 3D.* IU PTI supports 3D scanning, immersive visualizations, and 3D printing technology in use at IU. IU's distinctive collection of high resolution scanning devices allows to capture objects in minute detail including the "Old Oaken Bucket," anatomical parts of songbirds, the Showalter Fountain, and entire buildings. Staff of the Research Technologies Advanced Visualization Lab have, for example, digitized the entire IU Cinema inside and out. This allows the re-representation of 3D objects in immersive visualization and in 3D prints – blowing things up to review fine details or creating "shrunken" replicas of large structures. 3D printing also creates the opportunities for new forms of artistic creation, such as the 3D sculpture pictured here made by IU Associate Professor Nicole Jacquard.

Figure 4. Sculpture constructed with a 3-D printer, by IU Professor Nicole Jacquard

In all of these cases, IU PTI participates in the identification of needs faced by IU researchers, is responsible to the needs of IU researchers, and then invents technologies that solve problems for IU researchers. In the process, IU PTI solves problems for researchers throughout the world.

IU PTI's engagement in the research community also extends beyond its work with IU researchers. In fact, IU PTI frequently engages at the state and national level by providing services, engaging in and informing national research directions and priorities, offering services and education, and otherwise participating in the fabric of the national research community.

Recently, the IU PTI-affiliated Center for Applied Cybersecurity Research (CACR) was selected by the state of Indiana to provide services to secure the 2020 election. CACR's team of experts helped prepare election officials in all 92 Indiana counties for potential cybersecurity incidents that might occur around the 2020 general election and beyond. At the 2020 Election Administrator's Conference, the CACR team led a half-day "boot camp" and tabletop exercises in dealing with cybersecurity incidents through a grant from Indiana Secretary of State Connie Lawson.

IU PTI, largely through CACR, contributes to state and national cybersecurity in several other ways:

- CACR helps secure the US's cyber-borders by assisting US defense departments through engagement with the Crane Naval Surface Warfare Center, serving as a Department of Homeland Security-certified Center of Excellence in Cybersecurity, and training volunteers in the National Guard.
- CACR leads an annual NSF Cybersecurity Summit, which is one of the means by which the largest and most important NSF-funded research projects learn about and share best practices related to cybersecurity.

- CACR leads the Research Security Operations Center (ResearchSOC). ResearchSOC is unique as the only organization with the mission to provide operational cybersecurity services to NSF-funded facilities and projects while at the same time seeking to further research in cybersecurity. Funded by a $5M award from the NSF, ResearchSOC helps make scientific computing resistant to cyberattacks and helps secure the validity of US scientific research.

One particularly important component of IU PTI's service to the nation is its influence on national research priorities, as depicted in Figure 2. IU PTI's research and services activities: what drives IU PTI's activities, and how IU PTI drives Indiana University capabilities and national agendas.Some of this influence is exerted by participation in and leadership of government agencies and government advisory committees (see Appendix 13.14 for a listing). IU PTI-affiliated faculty and staff have often served in positions of national leadership in academic associations and organizations, conferences, workshops, and advisory committees to federal agencies. A few IU PTI-affiliated individuals have testified before congressional committees or served as temporary employees of federal funding agencies. Several IU PTI-affiliated faculty have been recognized for the distinction of their service and intellectual achievement by being named members of national academies, winning major honorary awards, best paper awards, and being awarded distinguished or endowed professorships at IU. Such awards and distinctions are tallied in Appendices 13.14 and 13.14.

By demonstrating new technologies and breakthrough computing innovations, especially at national and international conferences, IU PTI continues to influence the national research community and federal research priorities. This occurs in many venues, but perhaps most importantly and most consistently in The International Conference for High Performance Computing, Networking, Storage, and Analysis (SCxy series). IU PTI collaborates with other Indiana University entities (for example, the Luddy School and GlobalNOC) to display their computer science, informatics, cyberinfrastructure, and cybersecurity innovations at the annual conference. This conference serves as a testbed for development and demonstration of new technologies through various "challenge competitions." IU has won a total of four such events – as far as we know more than won by any advanced computing center other than the initial four NSF-funded supercomputer centers. SCxy also gives IU faculty and staff the opportunity to network with colleagues from other institutions working on projects such as the NSF-funded Jetstream or NCGAS. IU benefits from its participation in this conference and also contributes strongly to its management and execution. RT Associate Vice President Matt Link was elected to serve on the SCxy steering committee - the top-level organizing body for this conference - for several years. Link is the only member of the IU community to serve at this level of the SCxy organizational structure.

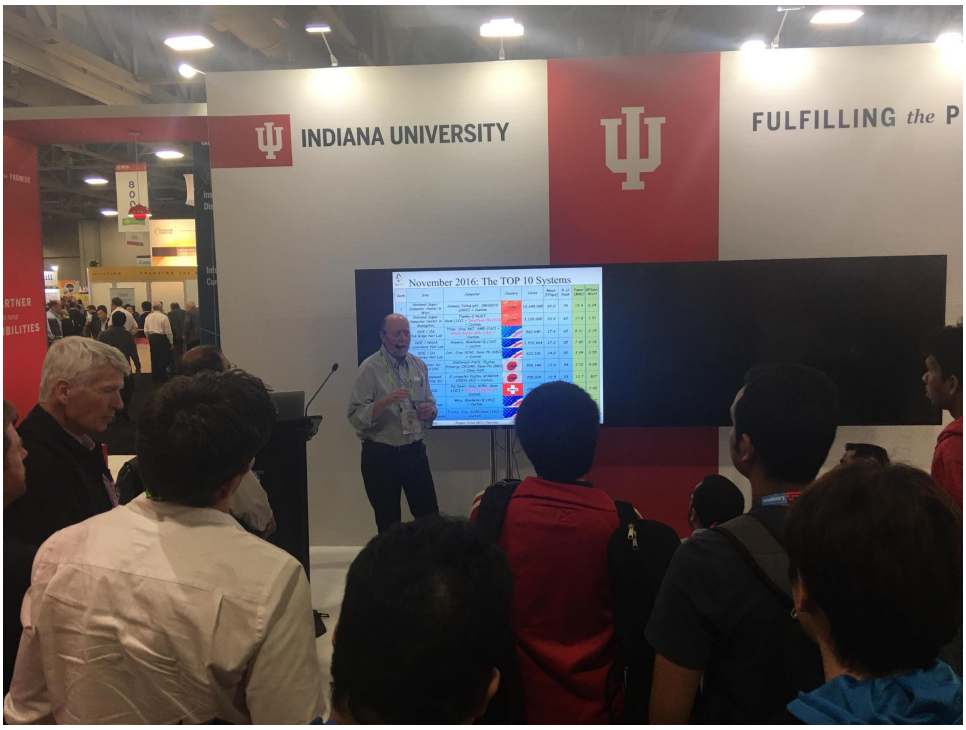

Figure 8. World renowned supercomputer expert Jack Dongerra giving a presentation at the Indiana University booth on opening night of SC16. The crowd spilled out into the aisles and neighboring booths.

IU PTI's leadership and competence to lead national agendas is evident in its success in receiving federal funding to offer services to the US research community. Many of the services mentioned earlier are offered by IU PTI via federal funding, which has a number of important benefits for IU and for the nation. Often these services are prototyped and demonstrated at national and international conferences such as the SCxy series. As mentioned before, IU PTI pursues grant funding when its leaders believe that it is the organization within the US best qualified to design and deliver a particular service; our unusually high success rate in having proposals funded shows that we are often right. So, the nation is served by some of the best experts available within our country – including our IU colleagues. On top of that, such federal funding creates a critical mass of expertise available within IU. As a matter of policy, IU provides funding for at least 10% of the salary of each IU PTI-affiliated staff member, so all of the expertise we bring to IU has at least a small amount of time funded by IU and allocated to serving the IU community.

IU PTI is unique among US advanced computing centers in its commitment to national and global education through leadership of an international free publication called *Science Node.* IU PTI organizes the fundraising for an innovative and popular e-publication called Science Node (sciencenode.org). Science Node is read by nearly 150,000 people, and offers reliable, engaging journalism about new scientific and technological breakthroughs made possible by advanced computing technology. Science Node is operated by the Information Technology Communication Office (ITCO) in the Office of the VP for Information Technology, and operates with journalistic independence under the guidance of an external advisory board. Because of that, Science Node is trusted as an authentic and accurate conveyer of excellent science journalism. IU PTI raises the money to pay Science Node staff. IU PTI-affiliated Centers and the IU GlobalNOC contribute roughly one-third of the funding for Science Node. The remaining two-thirds is provided by underwriting from colleges and universities throughout the US and the European Union, and that fundraising effort is led by IU PTI. Science Node's readership includes students, young professionals, and seasoned university experts; its ever-growing base of readers accesses Science Node content via Twitter, LinkedIn, Facebook, an email newsletter, and a constantly updated web

page. It is the only free publication that focuses so directly on the role of advanced computing technology in innovation.

5.2.2. IU PTI develops and deploys advanced computing infrastructure

Through IU PTI's success in winning grant and contract money, it creates new technologies (often) or transforms existing proofs of concept into widely used and robust research and development tools (very often). IU PTI has brought more than $136M in grant money to IU including two grants of more than $10M. Both accomplishments, within the context of IU, and of higher education generally, are simply exceptional and represent expertise in creating ideas, explaining their importance to funding agencies, and carrying out funded research so that the virtuous cycle of obtaining federal funding, using it well, and pursuing innovative directions for federally funded research persists.

Examples new technologies transformed into widely used R&D tools include the following:

- *Science Gateways.* Science Gateways are web interfaces and middleware that enable straightforward interaction for researchers with complex suites of software running on multiple advanced supercomputers and data resources. Science Gateways tie together diverse CI systems in ways that appear straightforward from the users' standpoint. In the area of Science Gateways, IU PTI has both invented a new technology and nurtured it to the point of becoming a widely used tool. CIRC leaders Marlon Pierce and Suresh Marru are Apache Foundation Fellows (the only people in IU PTI with this distinction) and the primary architects of the Apache Airavata software. Apache Airavata, one of the most widely used open source science gateway frameworks in existence, is responsible for dozens of science gateways in use in science and engineering applications. Many of these are hosted by IU on its cloud systems, while many others are operated by other universities, government research labs, and private manufacturing firms. As computing moves increasingly to interactive analyses, including advanced engineering in the private sector and defense-related design, Apache Airavata offers the unusual capabilities of supporting highly secure computations and features that enable recording and replaying interactive analyses.
- *Workflows for genome analysis.* Gone are the days when analysis of genomic information involved running one or two software packages. Today, genomic analysis today involves putting together multiple software packages, piping data from one to another, adjusting parameters and options, and then reanalyzing to obtain a rich understanding of the wonder that is life on this planet. The National Center for Genome Analysis (NCGAS) has emerged as a leader in the curation of "best of breed" software and assembly of tools into workflows designed to enable new insights from biological research. In the process, NCGAS has enabled the assembly of the genomes or transcriptomes (the full suite of RNA sequences assembled from the expression of DNA) for organisms of economic importance from the white pine to crustaceans at the base of the oceanic food chain, and from common animals like salamanders to endangered species found only in one small part of the Colorado River basin.
- *New tools for programming new hardware.* The use of Graphical Processor Units (GPUs) has transformed the hardware design and processing capabilities of supercomputers in the US and worldwide. In the US, exascale computers, which are capable of a thousand quadrillion mathematical calculations per second, are created with designs that depend on tens of thousands of GPUs. They are, however, quite difficult to program. OpenACC, with IU PTI's aid through RT, has become one of the standard programming tools to develop scientific applications that use GPUs effectively.
- *Software Assurance Marketplace (SWAMP).* The Software Assurance Marketplace is a suite of tools and a service that enable US researchers to create secure, hack-resistant scientific software. SWAMP, which operates as a combination software tool and platform for software, checks for

vulnerabilities in scientific software. One can easily upload software to a SWAMP instance running in the cloud and have those software packages evaluated automatically, or one can download "SWAMP in a box" and run it locally. SWAMP protects US scientific software, data, and results from bad actors.

In most of the above areas, IU researchers function as exemplars of world-class research leaders; IU PTI works to discover their needs, create proofs of concept solving problems, and then propose that the government make large-scale investments that serve national needs. OpenACC are the exception, where the IU PTI involved itself in a public-private consortium and then led an activity that involves little federal investment and yet benefits the US greatly.

IU PTI has also been a long-time leader in creating open source software, and in improving open source software released by others. To date, IU PTI has released new or improved versions of a total of 73 software titles.[20] Notable tools include a suite of software packages for management of data provenance, a number of programming and communication suites, and a large suite of bioinformatics software. For example, Trinity is the most widely used software package in existence for assembling sequences of RNA. It produces excellent biological results, but its authors were primarily biologists, not software engineers. Software performance experts from RT under the leadership of Director Robert Henschel rewrote important pieces of the software without changing the results it produced and made it run 8 times faster than it had previously. This meant a change from "one day to the next" in getting results to "results back multiple times in a working day," drastically altering how biologists could interact with their data.

IU PTI also operates hardware resources, software systems, and dedicated hardware/software environments designed to support particular functions. Throughout its existence, IU PTI has hosted a total of 68 major services, ranging from visualization systems to specialized software tools running on dedicated hardware. Thousands of students and visitors have seen compelling scientific and artistic works displayed on advanced visualization environments created by IU, such as the display wall shown at right, which shows of photographs of South African miners.

Many of PTI's notable major services have arisen from the collaboration of two or more centers on one project. The following examples illustrate the powerful synergy among centers; the collaborative relationships within IU PTI facilitates the creation of a whole that is more than the sum of its parts:

- *FutureGrid.* A distributed set of heterogeneous high performance computing (HPC) clusters and small supercomputers used to develop and test new software, FutureGrid was a breakthrough for IU PTI as its first individual grant award with a budget over $10M. It was also IU's first grant award for what the National Science Foundation calls "Track 2" systems: systems that are made available as a resource to the national research community and allocated and supported by XSEDE. FutureGrid, a collaboration between DSC and RT, provided resources for many important grid and cloud computers, and innovations created through FutureGrid were active from 2010 through 2015. The project was led by PI Geoffrey C. Fox, but the preparation of the proposal and implementation of systems in four different physical locations would not have been successful without RT's deep engagement.
- *Jetstream.* Perhaps IU PTI's most significant contribution to advanced computing hardware systems , Jetstream is the first NSF-funded cloud system for support of science and engineering research. Initially led by PTI Executive Director Craig Stewart, and continued under the leadership of PI David Y. Hancock since 2017, Jetstream was IU PTI's second grant award for more than $10M. Funded initially at just over $10M in 2015, Jetstream remains active today.

[20] In prior reports IU PTI has listed a tally of titles and different versions of the same title. In this report we have chosen to list simply titles, so for example the CREST / Open System Lab software called the "Boost Graph Library" represents one title but dozens of releases.

Additional NSF funding has brought the total federal investment in this system to nearly $15M. In the last half-decade, Jetstream has had an immediate impact on the national research community, as thousands of researchers have used this accessible, intuitive cloud system. Jetstream has been particularly important in fostering biological, earth science, and climate research in the US. Jetstream operates with the same philosophies and principles as commercial cloud systems – always on, continual improvement – but unlike commercial cloud systems, Jetstream was designed to serve research and educational purposes. Cloud computing is now a widely accessible tool for the NSF and the US open research community thanks to Jetstream, a multi-institution project led by IU PTI. Jetstream was led by RT but its success has depended upon collaborations with NCGAS, CIRC, and CACR.

- *XSEDE and its predecessor the TeraGrid.* The "eXtreme Science and Engineering Discovery Environment" is a goofy name for a tremendously important national resource. One of the most important national computing, storage, and support resources, XSEDE is *the* national advanced computing administration and support service for the NSF. It is the latest instantiation of four decades of NSF-funded delivery of the nation's most advanced cyberinfrastructure in existence. Beginning with TeraGrid in 2003, the NSF moved from a model of independent centers to a single administration and support organization. Since then, the NSF has funded one organization to be a front door to the many advanced computation, data analysis, and visualization systems it funds for the national research community. IU became a service provider as part of the TeraGrid in 2004. TeraGrid evolved into XSEDE in 2011, and IU PTI has played a role in these critically important national services. IU PTI has also played integral roles in the other major services made available to the nation via XSEDE: the experimental FutureGrid system in 2010, efforts in science gateways and national CI integration since 2011, and most significantly the Jetstream cloud system starting in 2016. No US unclassified organization has had a larger overall impact on advanced CI-enabled research in the US than XSEDE, and IU has provided its expertise in the service of US global competitiveness. Tens of thousands of researchers and students have used NSF-funded systems and services with the aid and participation of CIRC, DSC, CACR, and RT.
- *Open Science Grid*. OSG was in many ways the complement to TeraGrid and XSEDE. OSG was a national grid of computers focused on high throughput computing (HTC) rather than high performance computing (HPC) (supercomputers and clusters). OSG was designed in large part to analyze data created by the Large Hadron Collider. RT and CACR were involved in OSG from the predecessors of the OSG projects that began in 1999 up to the writing of this report.
- *Support for research leading to Nobel Prizes.* Through its involvement in TeraGrid, XSEDE, and the Open Science Grid, IU has been involved in projects that facilitated research leading to three Nobel Prizes:
    - The 2013 Prize for Physics, awarded jointly to Englert and Higgs for predicting the Higgs boson (analysis done via the Open Science Grid)
    - The 2013 Prize for Chemistry, awarded to Karplus, Levitt, and Warshel for the development of multi-scale models for complex chemical systems (software development and analysis supported by TeraGrid and XSEDE)
    - The 2017 Prize for Physics awarded jointly to Weiss, Thorne, and Barish for directly detecting gravitational waves (software development and analysis supported by TeraGrid and XSEDE)
- *Science Gateways by the dozen.* CIRC, RT, and CACR offer dozens of such tools for use by local, national, and international audiences. Key services include:
    - *Science Gateway Community Institute (SGCI).* SGCI is funded by the NSF to support and foster the growth of the science gateways community. SGCI is one of just three grant awards for centers called "NSF Scientific Software Innovation Institutes." Through SGCI, CIRC provides technical consulting and support services for science gateways; these services have supported the creation or enhancement of over 50 science gateways.

- *Science Gateway cybersecurity.* Custos, a collaboration between CACR and CIRC, will integrate and deliver a major security capability needed to operate science gateways to the community. CACR provides cybersecurity consulting and input on best practices for this NSF-funded project, bringing together CIRC's unique expertise in science gateways and CACR's excellence in cybersecurity.
- *Science Gateways Platform as a Service (SciGaP).* As a result of a major grant award from the NSF, CIRC and collaborating organizations at other universities provides a computing environment on which researchers can operate "turnkey" (configure and use) Science Gateways for use by the science community. As with most such projects, CACR provides security analysis and monitoring.
- *Jetstream as a Science Gateway host.* Many Science Gateways are hosted on Jetstream, the majority of which are built in CIRC's Apache Airavata software. Tens of thousands of people use these gateways.

Several other important services operated by IU PTI are primarily the result of the efforts of a single center, including the following:

- *Secure systems.* In 2005, IU was the first US university to have alignment with HIPAA (the Health Information Portability and Accountability Act) as the "default" for all its storage and computation systems, which mean that IU's advanced cyberinfrastructure can be used to analyze and understand identifiable patient data. Very few universities provide this as a general capability even today, and IU biomedical research has been greatly enhanced and accelerated as a result. The initial push for HIPAA alignment was the result of an important collaboration between RT and the IU School of Medicine, in which IU ran the data repository for an international collaboration studying Fetal Alcohol Spectrum Disorder (FASD). That project, funded by the NIH with Stewart as the PI, required IU's system to be HIPAA aligned to carry out the essential analyses required to enable better analysis of FASD.
- *Visualization Systems.* The RT Advanced Visualization Lab (AVL) promotes and supports the innovative application of visual technologies to enhance IU's research, education, creative activity, and community outreach missions. Systems implemented and supported by AVL:
  - *IQ-Walls.* These large-format, ultra-resolution displays for visualization and collaboration. These systems, developed and designed by AVL staff, offer modestly-priced and extremely high-resolution display facilities.
  - *IQ-Tables.* These 65-inch multi-touch monitors that can be reconfigured into table, drafting table, or landscape mode for exhibitions and multi-user engagement .
  - *Experimental virtual and augmented reality systems.* These include a suite of cutting-edge VR and AR technologies, including the Programmable Immersive Peripheral Environmental System (PIPES) mixed reality interface systems. By way of example, users of the PIPES system can walk through a 3D rendering of an ancient Roman Garden, feel the warmth of the sun on their face, feel the breeze in the air, and smell fresh flowers.

  Systems obtained from commercial manufacturers and implemented at IU by AVL:
  - *CAVE and BARCO Virtual Reality Theatre.* The CAVE was the first widely-used 3D immersive stereoscopic virtual reality system. So named in part because it was a "walk in" size facility, IU was one of the first universities to have this advanced VR system. IU's 10'-cubed CAVE system was a highlight of visualization activities at IU for many years, and was visited by many notables including, in days before IU PTI began, former USSR leader Michael Gorbachev. The CAVE was superseded in 2000 with a BARCO Virtual Reality Theatre on the IUPUI campus.
  - *Science on a Sphere.* This spherical display was developed by NOAA for presenting scientific and informational visualizations, and creating dynamic visual experiences.
- *Operation IceBridge*. Active from 2009-2019, Operation IceBridge sought to provide a highly accurate yearly picture of Arctic and Antarctic sea ice, ice sheets, and ice shelves, in order to

track their behavior and enable future predictions. In collaboration with the University of Kansas's Center for Remote Sensing of Ice Sheets (CReSIS) and RT, the project collected and processed hundreds of terabytes of data amassed as the team flew over the ice in Greenland and Antarctica. The mission used naval P-3 and DC-8 planes equipped with multiple radar systems and an IU-designed flying supercomputer called the Forward Observer to map surface snow accumulation, the thickness of the snow on top of the sea ice, and the terrain under the ice. Through Forward Observer, the research team was able to get a preliminary look at data as it was collected, making it possible for the team to make adjustments while still in flight.

- *Parallax Execution Model and HPX.* Professor Thomas Sterling and his colleagues created the Parallax Model of Parallel Computing Execution, the goal of which is to address the key challenges of efficiency, scalability, sustained performance, and power consumption with respect to the limitations of conventional programming practices. The Parallax model was realized in the HPX High Performance parallax software developed by CREST. A full version of HPX-5 software was released in 2015 at the SC15 conference in Austin, Texas.[21] While the US Department of Energy ultimately did not select HPX as a key component in the US exascale computing project, the Parallax model and HPX were influential in the design and development of software for exascale systems. This project was led by CREST during its heyday at IU.
- *Trusted CI: leading the NSF cybersecurity ecosystem.* Now in its seventh year of service, Trusted CI has been at the forefront of the NSF community in building a set of technical, policy, and cultural best practices to ensure the security of that infrastructure and the trustworthy nature of the science it produces. Trusted CI has provided security and security review services for more than 260 NSF projects since its inception in 2012, and over 300 hours of training to the community in 2019. CACR's ongoing leadership in protecting more than $7B in NSF-funded research was confirmed this past year with a $12.5M grant extension for the NSF Cybersecurity Center of Excellence (Trusted CI) for expansion of its activities. CACR is the lead organization for Trusted CI, in collaboration with the National Center for Supercomputing Applications, the Pittsburgh Supercomputing Center, Internet2, Lawrence Berkeley National Laboratory (Berkeley Lab), and the University of Wisconsin–Madison.

The list above offers examples of influence moving in two directions: national research needs influence IU PTI's priorities, and IU PTI's priorities influence the national research agenda. IU PTI has often helped define needs and proposed solutions that aid US research. In some cases, such as Operation Icebridge, IU PTI was able to propose and implement novel solutions to high priority national challenges that were otherwise unsolved by other research institutions.

5.2.3. IU PTI leads and supports the commercialization of IU-developed technology.

One of the original arguments for creating the initial set of Pervasive Technology Labs, and then for the transformation of PTL into IU PTI, was the aid and support that PTL and IU PTI provided to the Indiana economy. One aspect of IU PTI's support for the Indiana's economy while simultaneously supporting Indiana University itself is IU PTI's involvement in commercialization of technology invented at IU. A few key examples of such commercialization efforts include the following:

- *A new company created and then bought by Facebook.* IU PTI's most successful involvement in a spin-off company must be regarded as the success of Ryan Newton's company Cloudseal. Conceived while Newton was affiliated with CREST, Cloudseal was created through a SBIR (Small Business Innovation Research) grant award, and was not yet a year old before it was purchased by Facebook.

[21] https://itnews.iu.edu/articles/2015/indiana-university-announces-hpx-5-version-2.0-runtime-system-release-.php

- *Self-driving technology helping to power autonomous lawnmowers.* The Advanced Network Management Lab (ANML) participated in an autonomous vehicle competition run in 2004 by the Defense Advanced Research Projects Agency (DARPA). The initial challenge was to create a self-driving vehicle that could navigate a large obstacle course in the desert of the western US. A consortium of Indiana organizations worked together to create a self-driving version of a Jeep under the name IndyRobotics LLC. The IndyRobotics entry didn't win, but its self-driving software was picked up by an Indianapolis company that created and manufactured self-driving lawnmowers. That company was bought by MTD - the parent company of Cub Cadet, Troy-Bilt, Columbia, Yard Machines, and other brands, and so inventions by IU PTI have facilitated major innovations in lawnmower products used across the US and also sold internationally.
- *Bloomington-based analytics company – Chalklabs.* Chalklabs LLC is a small company in Bloomington, IN, started by students of IU professor and PTL fellow Katy Boerner. Chalklabs remains a successful and profitable business providing data analytics and reporting services to researchers and companies in Bloomington and across the US.
- *Radical new processors for supercomputers.* The work of Professor Thomas Sterling continues on in the private sector as well as the public sector. Simultac LLC is designing a radically new type of processor for potential use in everything from low-power sensor devices to exascale computers. In some ways, what Simultac proposes to do is create a second revolution in computer processors, like the one started by RISC processors in the 1990s. Simultac LLC has received two rounds of federal funding to develop its innovative technologies.

Throughout its 20-year history IU PTI has honed its skills in successfully moving its inventions into the private sector to benefit IU, the state of Indiana, and the US.

5.2.4. IU PTI enhances the growth of Indiana's economy.

IU PTI's contributions to the Indiana economy extend well beyond the commercialization of IU inventions. President McRobbie always lists IU's roles as research, education, and service to the state of Indiana (and by extension the US and the worldwide community). Such activities are important whether or not they lead directly to income for IU. Often activities to support and advance Indiana's economy do not; rather, they are ways for IU to give back to Indiana.

One of IU PTI's most immediate impacts on the Indiana economy of Indiana is job creation. IU PTI attracts talented, technically adept staff to Indiana, and keeps them happily employed and funded through competitive grants and contracts brought into Indiana from outside the state. Over the first 20 years of IU PTI's existence, grant funding has contributed 862 person-years[22] of employment to the Indiana University payroll. These employees live, shop, and pay taxes in Indiana. These are actual counts of people who work for IU as a result of grants and contracts led by IU PTI. Almost one thousand person-years of employment have been funded at IU as a result of IU PTI.

We can also estimate the indirect effects of grant and contract money brought to the Indiana through the IMPLAN methodology. IMPLAN estimates the number of jobs created through activities such as spending within communities of grant funded staff such as those working for IU PTI.[23] IMPLAN is the

[22] This is an exact figure based on how many people have been employed with grant funds by IU PTI since 1999.

[23] IMPLAN regional impact multiplier system (http://www.implan.com) estimates the total number of jobs created directly and indirectly as a result of grant income. It estimates, for example, how many jobs in the private sector of a given region are created as a result of having more customers in that region hired directly by out of state funding. One has to make a few assumptions to estimate full time equivalent jobs created in Indiana from IU PTI's grant

standard tool used by economic planners across the US to estimate impact of grants, contracts, and other government investments. Using the IMPLAN methodology, we estimate that IU PTI's collective efforts have created a total 2,100 years of employment in central Indiana since 1999.

IU PTI also offers direct support to companies located in Indiana and to national and international companies that have a major presence in Indiana. IU PTI has engaged in 11 partnerships with Indiana businesses of various sizes that were sufficiently involved that a contract, MOU, or nondisclosure agreement about the partnership was executed. Key examples include the following:

- *Aiding the high-tech manufacturing industries of Indiana.* V4I – the Virtual, Verification, Validation, & Visualization Institute – is a private-public partnership led by the Rolls Royce offices in Indianapolis. It aims to identify private sector problems in computer-enabled engineering and apply public sector solutions to those problems. IU PTI, and CIRC in particular, has aided V4I's development while also leveraging its relationship with V4I to obtain federal funding for commercialization of IU PTI-developed science gateway technology.
- *Open source tools used by private firms in Indiana.* Many open-source software tools created and distributed by IU PTI also support research and development in the private sector. Several Indiana industrial concerns make use of IU PTI-created open-source software, making good on the state's investment in IU and IU PTI. For example, the pharmaceutical companies located in Indiana have for many years made use of bioinformatics software distributed by IU.[24]
- *Research contracts with software companies.* Microsoft Inc. awarded IU PTI a contract of just over $1M for a project aiming to understand the roadblocks to adoption of commercial cloud technology in research, and how to overcome those obstacles.
- *Helping Cummins Inc. make its diesel engines more efficient.* IU PTI maintains significant engagement with the international diesel manufacturer Cummins, Inc, based in Columbus, IN. RT, in particular, aided Cummins in streamlining its workflows for combustion simulations in diesel engines, helping Cummins make more efficient diesel engines that release fewer pollutants into the air.

5.2.5. IU PTI aids the development of a strong STEM workforce in Indiana.

An excellent and capable STEM workforce is essential to US global competitiveness. IU PTI aids Indiana and the nation more broadly in employing and developing such a workforce. One way IU PTI does this is, of course, by employing a world-class STEM workforce itself, and by leading IU in the employment of a diverse workforce (a discussion of diversity in the IU PTI workforce is included in Appendix 11).

IU PTI helps develop a strong 21st century workforce in Indiana through educational experiences that begin in Hoosier grade schools and extend through postdoctoral education. To cultivate a high-tech adult workforce, one must begin by sparking children's interest in technology. One must also spark parents' interest in encouraging their children to pursue careers in STEM. IU PTI has offered thousands of outreach and educational events attended by people of all ages. Since the very first outreach event on August 21, 2000 – a public reception and set of talks announcing the first concrete steps in moving PTL from vision into reality. Annual events like the camps are part of that effort; talks, tours, demonstrations

successes. First, not all of the grant funds obtained by IU PTI stay inside the state of Indiana; purchases of computing hardware, for example, typically involve sending money to vendors outside the state. Subcontracts on multi-party grant awards may also send grant funds out of state. Thus, we assume that one-third of the grant funds awarded to IU PTI have stayed within Indiana. We also assume also that one FTE is equivalent to four of the "jobs" that IMPLAN estimates to have been created per unit of external funding.

[24] Note that one of these companies - Lilly, Inc. - has no direct relationship with the Lilly Endowment, Inc. The Lilly Endowment was created as a trust to advance the quality of life in Indiana by the first-generation offspring of Dr. Eli Lilly, and has, since its inception, operated independently of the pharmaceutical company.

at the state fair, displays at state parks, and other avenues round out IU PTI's bid to encourage Hoosiers to pursue careers in STEM.

Some of IU PTI's activities are focused specifically on young people. A few examples of IU PTI programs designed to interest people in STEM fields and the importance of technology include the following:

Figure 2-3. The Ready, Set, Robots! Challenge allows campers the opportunity to show-off the programming skills they have learned to friends, family, and other campers.

- *Ready, Set, Robots!* In 2005, IU PTI initiated a summer camp called Ready, Set, Robots!,[25] and has held it every year since. As part of this camp, junior high and high school students learn computer programming, problem-solving skills, critical thinking, and teamwork. Students also gain public speaking experience, respect for equipment and facilities, and insight into working "green" in IU Bloomington's LEED-certified Cyberinfrastructure Building.
- *Security Matters Cybercamps.* Since 2016, CACR has run a day camp for kids 7-8+ focusing on all things cybersecurity. Security Matters Cybercamps help teach kids safe computing practices from the start while also interesting them in technology and associated careers.

IU PTI's leadership in education continues on through the college experience at IU. Students in many disciplines who are on their way to professional careers participate in IU PTI's Research Experience for Undergraduates (REU) programs. Direct involvement in authentic research is one of the best ways to interest young people in science generally and in cyberinfrastructure for scientific research in particular. The Jetstream REU program led by Dr. Winona Snapp-Childs, manager of RT's Collaboration, Engagement, and Support Group, has been particularly successful in this regard. Since 2017, the program has engaged 21 undergraduates in projects that capitalize on IU's leadership in fields like bioinformatics, cybersecurity, data visualization, and advanced media. Each year, the program culminates in submission

[25] UITS at Indiana University. (2015). *Ready, Set, Robots! Camp*. Available from https://www.youtube.com/watch?v=zWh9hWf0rBM&feature=youtu.be&list=PLqi-7yMgvZy8xB64_0-O7PId_uzTFy9PO

to a national conference, and some students have been recognized with prestigious awards, including Best Paper and Poster awards. Several participants in REU programs have reported that the program was integral in prompting them to enroll in graduate study, and some of those in Computer Science. Jetstream itself has been an important contributor to STEM education. Jetstream has served more than 6 times as many students as any of the other similar sized NSF-funded computing resources.

The faculty and staff affiliated with IU PTI also teach courses at IU, and supervise students who receive Master's and Ph.D., particularly in the Luddy School of Informatics, Computing, and Engineering. As one example, CIRC's Marlon Pierce and Suresh Marru co-instruct the course "Applied Distributed Systems," which is offered through the Luddy School to graduate Computer Science students as a special topics course. The course has been offered at least once per year since 2016 and has been taken by over 125 students.

A Ph.D. represents the highest level of mastery within most disciplines, and is the highest degree conferred at most research universities. People who earn a Ph.D. not only master what is known in a particular field, but also make important original contributions to research in that field. Through its first 20 years, IU PTI has supported and, in many cases, supervised a total of 73 graduate students who have been awarded the Ph.D. IU PTI also helps recruit people to the US for advanced education and training. Graduate education is one way that IU PTI has attracted international talent to come to and stay in the US. Many of the graduate students getting degrees from IU with support of IU PTI have remained in the US, strengthening the US STEM workforce.

IU PTI's outreach efforts reach thousands of people per year, many in Indiana, and it has engaged hundreds of students through education and REU programs. Through these efforts, IU PTI keeps Indiana, and the nation, abreast of Indiana University's research efforts, and encourages Indiana youth to consider STEM disciplines as college majors and career choices.

5.2.6. IU PTI stimulates IU's innovation pipeline.

IU PTI began as three centers: the Data to Insight Center, the Digital Science Center, and the Center for Applied Cybersecurity Research. It grew to four with the Research Technologies Division of UITS in 2009. It has since grown to its current seven centers by creating new centers – sometimes from scratch, but more often by nurturing the growth of single-leader labs into large, multi-leader centers. The current total reflects the creation of four new centers and the closure of one:

- The HathiTrust Research Center (HTRC) started out as a research project within the Data to Insight Center. The initial question was "how can we create a secure repository containing the millions of books from the Google book project that allows researchers to do text analysis and extract data about the texts without retrieving contents of books (and violating copyright laws)?" From this began the nascent service to support digital humanities research within the Data to Insight center, and the evolution of HTRC into a significant center in its own right.
- The National Center for Genome Analysis Support (NCGAS) started off as one bioinformatics specialist, an idea, and a grant proposal funded by the NSF. With such a start NCGAS simply sprang into existence and has expanded to its current nationwide reach.
- The Center for Research in Extreme Scale Computing (CREST) was promoted from its status as a lab within the Digital Science Center with the recruitment of Professor Thomas Sterling. CREST was, for a time, a great success for IU, bringing over $20M in grant funding to the university and creating many important innovations in computer science. CREST was disbanded (as explained elsewhere in this document) in 2018.
- The Cyberinfrastructure Integration Research Center (CIRC) was created in an unusual way – the promotion of what had been a management group within RT into its own center.

IU PTI continues to foster innovation and incubate new research organizations within IU, such as the recently created Crisis Technologies Innovation Lab (CTIL) and the eLearning Research and Practice Lab. When it comes time to bring a disband a center or lab, IU PTI facilitates the process while also providing employment continuity for technical staff.

These many IU PTI-affiliated centers offer services directly to the IU community at no cost to users through funding provided within IU from OVPIT, the Luddy School, the Office of the Vice President for Research, the Office of the Vice Provost for Research, and the IU Libraries. That is, through IU PTI, the IU community has access to a group of professionals so good that they are the top experts serving the nation with services deemed critical by federal agencies such as the National Science Foundation, Department of Homeland Security, Department of Defense, Department of Energy, and the National Science Foundation. Such services aid the IU community generally in developing new areas of expertise and intellectual accomplishment.

IU PTI has contributed to the growth of new areas of excellence for IU in many ways over its two decades, most recently and most specifically in the areas of Artificial Intelligence (AI) and hypersonics defense technology. While AI is hardly a new area of computer science research, having begun in the 1950s, it has recently increased as a priority for research and investment. IU PTI-affiliated faculty in the Luddy School are deeply involved in the new Indiana University Artificial Intelligence Institute – particularly D2I Director Beth Plale and DSC Director Geoffrey Fox. CACR Director Von Welch is leading efforts to integrate AI techniques into cybersecurity, and RT is providing new advanced computing systems designed to support AI tool development and use of AI applications.

IU PTI plays a critical role in IU's capacity-building in engineering and defense-related activities. The first two chairpersons of the Department of Intelligent Systems Engineering were DSC Director Geoffrey C. Fox and D2I Associate Director Martin Swany. Hypersonic weapons defense is a new area of focus for IU, IU PTI, and the Luddy School Department of Intelligent Systems Engineering. These weapons, which travel at more than 5 times the speed of sound, are highly destabilizing. During the Cuban Missile Crisis of 1962, the US and USSR had more than a week to deescalate a life-threatening situation. By contrast, a hypersonic weapon launched from a submarine could wipe out any US city in under 20 minutes. The impact of such capabilities is obvious, and the US must develop its ability to defend against such weapons. With funding support from the Luddy School and IU PTI, IU is working to compete for grants and contracts related to hypersonic defense. This capacity-building has been going on under the leadership of IU Bloomington Vice Provost for Research Jeff Zaleski, and will likely continue for months more before IU receives its first contract or grant in this area. Still, this capacity-building is essential if IU is to be involved in protecting against hypersonic weapons. IU PTI has emerged as IU's top asset in development of technologies relevant to hypersonic weapons defense efforts.

In a more general sense, IU PTI provides a number of central services that enable each center to maximize its productivity. These services include:

- *Pre-award support for grant preparation.* Perhaps IU PTI's most critical service to centers, "IU PTI Central" supports grant preparation through editing assistance, budget assistance, and critical reading and evaluation of draft proposals. IU PTI has an unusually high success rate with its proposal submissions as a result.
- *Education, outreach, and training activity support.* IU PTI, the Office of the VP for Information Technology, and the Luddy School of Informatics, Computing, and Engineering have staff who support education, outreach, and training events. When an individual center, a lab, a group of centers, or IU PTI all together wish to put on an event, there are people available to help plan and put on such an event.
- *Public relations, publicity, state and federal relations, and reporting.* Communicating about what IU PTI does is a critical part of its sustainability. IU PTI staff and IU staff generally provide

expertise and assistance in these important communication roles, ensuring that IU PTI messaging is effective, clear, accurate, and with the highest ethical standards and well within all relevant legal regulations.

- *Branding.* IU PTI has, after 20 years, earned a national reputation for excellence among the advanced research computing community. The name connotes IU PTI's reputation for being prudent and effective at accomplishing its goals. New centers and labs automatically inherit this reputational advantage – one gained over two decades – even though those new labs and centers might only be a year old.[26] This has been demonstrated time and again to increase attention given by the national research community and government to the innovations we create, and to aid the competitiveness of individual researchers, labs, and centers affiliated with IU PTI when competing for grant and contract funds.

Beyond supporting centers and labs, IU PTI has also supported accomplishment and promotion of its affiliated faculty. Certainly each of the following promotions would have occurred without IU PTI's existence, but support and facilities by IU PTI have we believe accelerated advancement of many of its affiliated personnel, such as:

- The Luddy School of Informatics, Computing, and Engineering has two faculty members at the Distinguished Rank. Geoffrey C. Fox was recruited to IU to become one of the initial leaders of IU PTI and rose from Full Professor to be the Luddy School's first ever Distinguished Professor. Katy Boerner arrived at IU as an Assistant Professor, and has risen to Distinguished Professor and has been named the Victor H. Yngve Distinguished Professor of Engineering and Information Science. Early on Distinguished Professor Boerner received financial support as a fellow of the Pervasive Technology Labs.
- Beth Plale arrived at IU as an Assistant Professor and was been promoted to the rank of Full Professor as of the time she took partial leave from IU to serve as a staff member and policy expert at the National Science Foundation.
- Associate Professor Judy Qiu Fox came to IU as a postdoctoral fellow and rose through the ranks to professional staff member, Assistant Professor, and then Associate Professor with tenure.

5.3. A promise kept

In his letter submitting IU's proposal for second-round funding, IU President Michael A. McRobbie wrote that in 50 years we might look back and see the creation of IU PTI as one of the critical turning points in the development of high-tech research at Indiana University. Twenty years on, IU PTI can claim an important role in the evolution of Indiana University as a high-tech university. IU PTI's impact ranges from its grant success, funding expansion of the local high-tech workforce, value to the Indiana economy, and increasingly direct value to the IU community.

IU PTI and IU can claim that a promise made in 2008 is now a promise kept. In the 2008 proposal to the Lilly Endowment, IU committed that at the end of the 2nd round of financial funding for IU PTI that it would be maintained on the basis of external grants and contracts and a small amount of IU support. IU PTI has more than been sustained; rather, it has thrived and expanded its scale and its effect carefully and prudently. The promise to the Lilly Endowment has, indeed, been kept.

[26] In the movie *The Princess Bride*, one of the main characters – the Dread Pirate Roberts – turns out to be less a person than a brand name. The role is handed down from person to person so each new "Dread Pirate Roberts" inherits the reputational advantage created by their predecessors. IU PTI's brand name functions a bit like that.

6. Highlights of our 21st year

Thus far we have focused exclusively on activities and accomplishments of our first two decades. However, as we were wrapping up our 20th year there were projects afoot that were so exciting that we just couldn't keep ourselves from writing about them here. Among other things, the story of Jetstream is simply not complete without talking about Jetstream2. Plus, we're all a little tired of report writing, and no one was enthused about the idea of writing an annual report for Fiscal Year 2020 independent of the present report. So in this section we present highlights of the first few years of our 21st year, followed by updates to those metrics that have changed since the day of our 20th anniversary on September 22 2019. (Highlights of the activities of particular centers and labs are provided in Section 7.

- *COVID-19 response.* IU PTI has proved out its capability to react quickly to local, regional, and national needs with its involvement in the fight against the novel COVID-19 virus. Prominent among IU PTI's engagements in this fight are:
    - IU PTI was a charter member of an organization called the US COVID-19 HPC Consortium[27] – a public-private collaboration bringing together dozens of supercomputers and cloud systems with a total of more than 600 PetaFLOPS of processing capability to support research in the fight against COVID-19. Jetstream is among the systems being used in "rapid response" research related to this fight.
    - The DSC created and operated the software used on supercomputers of the Pittsburgh Supercomputing Center to run overnight predictions and simulations of the spread of COVID-19 under different scenarios, helping to inform public health recommendations for fighting COVID-19.
    - DSC Director Geoffrey Fox and Associate Director Judy Qiu Fox are part of a newly funded collaboration called the Global Pervasive Computational Epidemiology project. This project, funded by the NSF, aims to develop new strategies for controlling epidemic outbreaks, supporting real-time decisions and analysis during epidemics such as the current COVID-19 pandemic.
    - The eLearning Research and Practice Lab received significant grant support to lead a survey of all undergraduates and instructors across all several universities. The results of this "Mega-Study of COVID-19 Impact in Higher Education"[28] are already published and guiding the response of IU and many other institutions of higher education nationally in responding to the COVID-19 pandemic.
    - The Crisis Technology Innovation Lab has created and is operating regional and national dashboards to inform the public and civil protection officials in understanding and reacting to the COVID-19 pandemic.
    - NCGAS offers consultations to medical scientists, biologists, and bioinformaticians who are involved in COVID-19 research.
    - RT offered critical support to IU in the early weeks of response to the pandemic, as all IU students were sent home to take their classes remotely in March of 2019:
        - RT's windows-oriented virtualization service IUAnyWare group was expanded to enable students and researchers working remotely to use software otherwise available to them only on campus. Secure exams were also offered via IUAnyWare.
        - RT made all statistical and mathematical software licensed by IU available to students free of charge from April to June 2020 to help with learning from home as necessitated by IU's response to COVID19.

[27] https://covid19-hpc-consortium.org
[28] https://osf.io/n7k69/wiki/home/

    - These steps allowed IU students to work from home as effectively and as easily as possible to complete the unprecedented remote learning experience that was part of IU's response to COVID-19.

- *Jetstream2.* IU PTI has been awarded a grant from the National Science Foundation to deploy Jetstream2, an 8 PetaFLOPS distributed cloud computing system to support on-demand research, artificial intelligence and enhanced large-scale data analyses for the nation. This is an award with an initial budget of $10 million dollars. The structure of this award is designed to fund Jetstream2 as a national service for a decade with a 10-year budget that should easily exceed $30M. In the press release about this exciting project, PI Hancock stated, "We intend Jetstream 2 to be a democratizing force within the NSF ecosystem, allowing researchers and educators access to cutting-edge resources regardless of project scale." Jetstream2 will continue the foci on life sciences research, education, and earth sciences research that characterized the original Jetstream system. In addition, this system is designed to support interactive use of AI software and the development of new AI tools. "AI for everyone" is one of the themes of Jetstream-2. Jetstream's focus on AI is in part informed by the development of IU's new Artificial Intelligence Institute, and will in turn offer IU researchers and the AI Institute computing resources to support and further their research. Jetstream2 will keep IU on the map of national services for the next decade to come with clarity and certainty for potential users, and with security of roles and funding for the dedicated staff who make the Jetstream program so effective. Jetstream2 is a first for IU: the first time that IU PTI has received major national funding for cyberinfrastructure system, and based on success of a first award received funding for a follow on and even larger system. This is *exactly* what the largest supercomputer centers in the US have done decade after decade to stay at the cutting edge of the nation's research community. Jetstream2 is led by PI David Y. Hancock and Research Technologies, and includes involvement from CIRC, CACR, and the Office of the Executive Director.
- *A major jump in the readership of Science Node.* Science Node experienced a major jump in its subscriptions during the spring of 2019 – adding more than 143,866 new readers. One reason for this was tremendous early coverage of how advanced computing was enabling the US and the worldwide community to react to and fight the COVID-19 pandemic. Another is the publication's long-running series on woman leaders in advanced computing, and how they arrived in careers in computing and places of prominence in the field.
- *Formal participation in hypersonics research and development.* Thanks to IU PTI leadership, IU became one of the founding members of the Military-Academic Center for Hypersonics (MACH). MACH is a consortium of universities in Indiana and in several other states that pursues research and development to help protect US citizens form the danger of hypersonic weapons. IU PTI has within the MACH collaboration a particularly close relationship with the University of Notre Dame, which has some of the fastest nonclassified wind tunnel facilities in the US. IU PTI is aiding researchers at Notre Dame in analyzing data from their wind tunnels.
- *Support for Cancer Research.* IU PTI has formalized an agreement to host a computer cluster for the not-for-profit organization Cancer Computer.[29] IU PTI will provide facilities and support for this international effort to find cures for many types of cancer.
- *Incubation efforts continue.* Luddy School professor Dr. Martin Swany and CACR Director Von Welch have proposed the creation of a Systems Assurance and Integrity Lab (SAIL). This relationship is modeled on the IU PTI lab concept and allows the two organizations to benefit from their complementary cybersecurity skills in outreach and grant competitiveness. Once approved, this will mark the addition of the third new lab affiliated with IU PTI in two years.

[29] https://www.cancercomputer.com

- *IU's first engineering baccalaureates.* IU PTI has played an essential role in the creation of IU's engineering program. At spring graduation in 2020, the first recipients of an undergraduate degree in Engineering received their diplomas from the Luddy School.
- *Rectifying the effects of systemic discrimination.* In response to national, statewide, and local events, IU PTI has engaged in an open discussion of what we can do to help bring an end to the effects of systemic racism and discrimination of all kinds in the US. A particular focus is what has been successful in the past in increasing the diversity of the IU PTI workforce and what we can do to expand that success in the future.
- *IU recognition of IU PTI and its affiliated centers.* Indiana University has a policy on approval of the words "Institute" and "Center" in the titles of organizations, and a classification system for such entities. "University level" is the highest such level, indicating impact and importance to IU as a whole. IU PTI is now recognized as a university-level institute. CACR is recognized as a university-level center. NCGAS is now recognized as a Bloomington Campus center – "campus level" being the second highest level of importance within IU's classification system.

Another highlight relevant to IU PTI is the appointment in the spring of 2020 of Dennis Groth as Dean of the Luddy School of Informatics, Computing, and Engineering. Together with newly appointed Finance Director Jill Piedmont, and longstanding Luddy leaders Associate Dean for Research Kay Connelly and Erik Stolterman, the 2020 Luddy School leadership team is instigating a new era in deepened collaborations with IU PTI. This has included commitment to create new IU PTI-affiliated centers and the codification of a Memorandum of Understanding that establishes consistent approaches to distribution of funds, which has the impact of facilitating collaborative research activities.

Metrics in some areas have not changed since the 20th anniversary of PTI in September of 2019. A few have. The few metrics updated to the end of FY2020 (June 30, 2020) follow in Table 3.

Table 3. Key metrics of accomplishment for the Indiana University Pervasive Technology Institute up to the end of Fiscal Year 2020 – most of our 21st year of existence.

Metric	Total from inception to end of June 2020
Creation of products	
PTI Technical Publications	1506 total; 1301 peer-reviewed
Data sets published [30,31]	179
Major services (added Big Red 3[32] [###___])	72
Grant successes	
PTI grant and contract total from federal sources to date	$131,449,586
PTI grant and contract total from non-federal sources to date	$11,064,747
Total grants and contracts for IU PTI	$142,514,333
Impact on employment in Indiana	
Person-years of employment created directly within IU PTI / Indiana University (actual grant headcount)	917 FTE person years

[30]Costa, C.M., J.A. Wernert, D.F. McMullen, C.A. Stewart, P.D. Blood, R. Sinkovits, S. Mehringer, R. Knepper, G. Rogers. 2020. Dataset: XSEDE Return on Investment Data and Analysis (July 2014 to August 2019). http://hdl.handle.net/2022/25407

[31] Ping, R. and T. Miller. 2020. Dataset: Indiana University Pervasive Technology Institute Education, Outreach, and Training Events through 20th Anniversary (22 September 2019). http://hdl.handle.net/2022/25793

[32] https://kb.iu.edu/d/aoku

Job-years of employment in the State of Indiana created as a side effect of IU PTI grant awards as estimated by the IMPLAN methodology	2,195 job-years
Science Node readers	143,866

As of the end of FY2020 (30 June 2019), there were a total of 121 FTEs working in IU PTI-affiliated centers: 67 FTEs were funded with university monies (most of these in RT). Within IU PTI, a total of 54 FTEs were supported by external contracts and grants as of the end of FY2019. In the figure below, RT is shown separately from the other IU PTI centers because it has such a significant set of responsibilities to IU funded by institutional monies. Of the grant- and contract-supported staff in RT, most are engaged in collaborative projects that involve one of the IU PTI centers or which were obtained with the aid of IU PTI in some fashion.

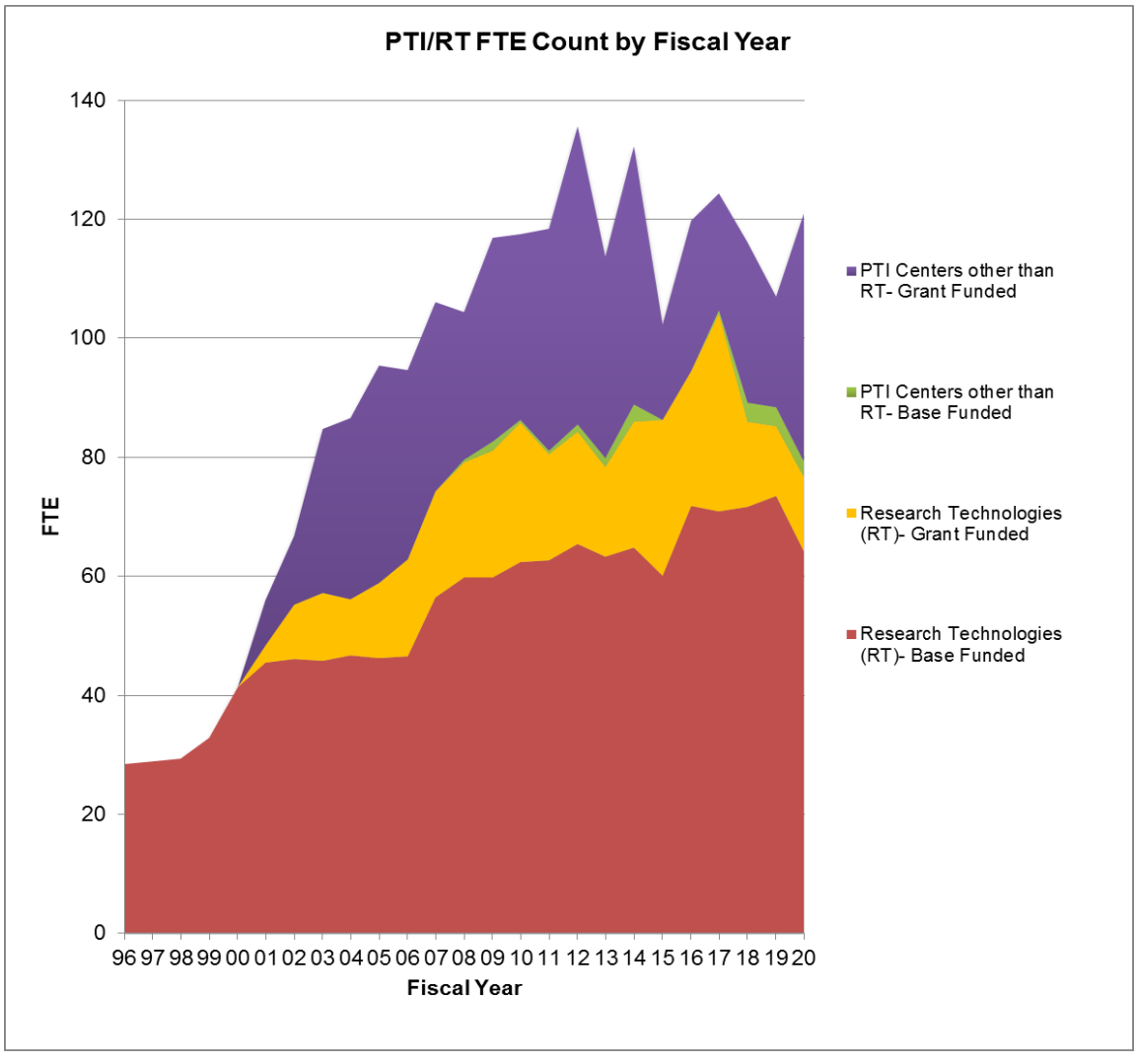

Figure 5. Personnel and funding for the Pervasive Technology Institute showing base-funded and grant-funded staff, as of June 30 2020

7. Centers and their accomplishments

This report has been focused on the aggregate accomplishments of IU PTI as a whole, but at the end of the day, its accomplishments happen at the level of centers or of multiple centers working together. It is not possible to summarize IU PTI's work without giving due credit to the various centers. Rather than focus on quantitative tallies of papers or grant proposals, the narratives below focus on the qualitative character of the research programs of each center or lab. These narratives begin with those centers active as of IU PTI's 20th anniversary, followed by a summary of the activities of labs and centers that have come and gone.

7.1. Currently active centers

The Center for Applied Cyberinfrastructure Research (CACR). Under Welch's leadership, CACR has developed an international reputation for leadership in cybersecurity theory and practice, with a focus on first principles of cybersecurity, security of scientific applications and data, and collaborations with federal defense agencies. Designated as a Center of Excellence by the Departments of Homeland Security and Defense, CACR has achieved an important IU objective of ongoing cooperative agreements with the Crane Naval Surface Warfare Center located south of Bloomington, IN. CACR is currently advising the state of Indiana regarding cybersecurity for the 2020 elections. Most recently, CACR has been named a university-level center and now reports jointly to the Vice President for Research. As part of this change, CACR Director Von Welch was promoted and now reports jointly to the Vice President for Information Technology and the Vice President for Research. A clear success story, CACR has achieved a position of singular national leadership, prestige, and accomplishment under the leadership of Von Welch and aided by its affiliation with IU PTI.

The Digital Science Center (DSC). DSC is the oldest of the current centers, starting as the "Community Grids Lab" when Dr. Geoffrey Fox first arrived at IU as PTL's new lab director. The Community Grids Lab evolved into the Digital Science Center in 2008 with the integration of Andrew Lumsdaine's Open Science Lab, the creation of Judy Qiu Fox's SALSA Lab (Service Aggregated Linked Sequential Activities), and the affiliation of the CNets Lab of Professor Fil Menczer. Today, affiliated faculty include Director Geoffrey Fox, Assistant Director and Associate Professor Judy Qiu Fox, leading AI expert David Crandall, and Adjunct Associate Professor Gregor von Laszewski. DSC has been the most prolific of all IU PTI-affiliated centers regarding production of scientific papers, graduation of students holding PhDs, and creation of new concepts. DSC has been particularly prolific in generating and demonstrating new concepts in grid and distributed computing. From message-based web interaction systems to integration of big data and high-performance computing, DSC has been at the forefront of inventions that are subsequently widely adopted in computer science and in practical, everyday applications of computing. Today, DSC foregrounds efforts to bring together high performance computing (HPC) and big data/cloud computing to aid advances in AI.

DSC holds distinctions within IU PTI, the university, and the world. DSC Director Geoffrey C. Fox was PI of the NSF FutureGrid grant award to IU PTI - the first grant award in excess of $10M and an innovative distributed system for developing grid and cloud software. Dr. Fox was the first faculty member in the Luddy School of Informatics, Computing, and Engineering to be promoted to the rank of Distinguished Professor. He was also the inaugural chair of the Department of Intelligent Systems Engineering. Lastly, he has been awarded one of the two most prestigious awards given to anyone affiliated with IU PTI: the 2019 IEEE-ACM Ken Kennedy Award recognizing his contributions to computer science and HPC.

The Data to Insight Center (D2I). The Data to Insight Center is run by Professor Beth Plale, who came to IU as an Assistant Professor in 2001. D2I was established as an IU PTI-affiliated center, with Dr. Plale

as IU PTI's Science Director, as part of IU PTI's formation. D2I is directly responsible for three widely used concepts in computer science and its applications:

- Science Gateways. Science Gateways are web front-ends linked to complex middleware that allow the orchestration of complicated analysis and simulation tasks across high speed networks using many supercomputers simultaneously. The most powerful initial demonstration of this important concept was a system called LEAD – Linked Environments for Atmospheric Discovery – a system for analysis and prediction of tornado paths. This project, led by University of Oklahoma Professor Kelvin Drogemaier (now Director of the White House Office of Science and Technology Policy) and involving PTL Science Director Dennis Gannon, was a critical "proof of concept" leading to the widespread use of Science Gateways today.
- Tools for FAIR data. One of the critical concepts in data science today is "FAIR," which holds that data should be Findable, Accessible, Interoperable, and Reusable. D2I was creating tools for FAIR data before FAIR was cool, and remains one of the most important sources of software and concepts about FAIR data in the US.
- Data Capsules and non-consumptive research. Professor Plale invented the concept of "non-consumptive research," that is, research and analysis of texts such that one received back as research results tallies of word use, maps of word use, quotes, etc., but without delivering enough of the copyrighted material to the researcher that one could reassemble and "consume" it as a written work. This, and the creation of "secure" data capsules led to the foundational concepts and services of the HathiTrust Research Center. HTRC was created initially as a project within, and then a subunit of, D2I, and since 2019 has been an independent center (see below).

D2I is a leader in developing new concepts in computer science, data science, and integration that have led directly to tools now used widely in the sciences and humanities. D2I is so far also the only IU PTI-affiliated center to develop and spin off a new center. As of the writing of this report, Professor Plale spends much of her time working at the NSF doing policy analysis and creation related to Data Policy and public access. Dr. Martin Swany has aligned his activities with D2I and focuses on advanced computing and communications related to scientific and practical applications, including the detection of and defense against hypersonic weapons.

NCGAS - National Center for Genome Analysis Support. Led by Dr. Sheri Sanders, NCGAS was created at the suggestion of a federal funding agency program officer, who pointed out to Craig Stewart the tremendous national need for expert bioinformatics software support and consulting. NCGAS's mission is to "...enable the biological research community of the US to analyze, understand, and make use of the vast amount of genomic information now available. NCGAS focuses particularly on transcriptome- and genome-level assembly, phylogenetics, metagenomics, transcriptomics, and community genomics." Started in 2011 with funding from the BIO directorate of the National Science Foundation, NCGAS has offered consulting services to researchers in 44 U.S. states and Puerto Rico. NCGAS distributes hundreds of different software titles in the area of bioinformatics and genome analysis. As of 2020, NCGAS supports 315 versions of 215 software packages across IU clusters, XSEDE Jetstream, and XSEDE Bridges. In the last nine years, NCGAS has held 165 training and outreach events, serving over 6500 researchers through free training.

One of NCGAS's important services involves interacting with clients throughout the US. NCGAS serves a large number of researchers and students from EPSCoR states, which receive little funding from the NSF relative to other states. Through its funding from the NSF, NCGAS has been instrumental in enhancing research and expanding possibilities for discovery throughout the US. NCGAS is also unique among IU PTI-affiliated centers in that the majority of its funding comes from the NSF BIO directorate. NCGAS has also been involved in a variety of research activities funded by the National Institutes of Health and at this point has received funding to participate in more projects funded by the NIH than any other IU PTI-affiliated Center.

CIRC- Cyberinfrastructure Integration Research Center. CIRC's mission is to "accelerate research, discovery and collaboration through the creation, integration and operation of user-centric cyberinfrastructure that benefits scientific communities." CIRC traces its roots back to the hiring of its current Director, Dr. Marlon Pierce, by Professor Geoffrey Fox at DSC, where Pierce was instrumental in developing middleware to realize the potential of the concept of science gateways. At DSC, Pierce developed his own subgroup, which eventually moved as a management unit into RT. Pierce's group, originally called the Science Gateways Research Center, became an IU PTI-affiliated Center. The group's initial focus was on expanding tools for and use of science gateways, which are designed to help communities of researchers use high-performance computing resources and advanced cyberinfrastructures to pursue common scientific goals. Its portfolio expanded to include responsibility for IU PTI's work in Campus Bridging, which includes the bridging of campuses to larger-scale research ecosystems, and bridging within campuses, between centrally managed research computing facilities and those who use them. CIRC, in collaboration with D2I, is also working with the Research Data Alliance to develop digital object architecture implementations that make scientific data easier to find and more accessible, interoperable, and reusable (FAIR). CIRC leads within XSEDE in its implementation of and support for science gateways and campus bridging, and also is a co-lead in a national effort called the Science Gateways Platform as a service (SciGaP) project. Today, CIRC supports the operation of more than 40 science gateways, and is also a leader in the open source software community. Apache Airavata – the open source software behind CIRC's science gateways – is an official Apache Foundation project, and Marlon Pierce and Suresh Marru were the first two people at IU named Apache Fellows.

HTRC – HathiTrust Research Center. HTRC is IU PTI's most critical and valuable service to the US humanities community. HTRC is also unique within PTI in that it is a fully-fledged center that spun off from another IU PTI-affiliated center (D2I, as described above). The mission of the HathiTrust Research Center (HTRC) is to provide infrastructure, tools, and services to support Text Data Mining of the HathiTrust (HT) corpus, a collection of more than 17 million volumes, of which more than 11 million are still protected by copyright. The primary operational foundation for HTRC's activities has been funding from HathiTrust, a membership organization operated by the University of Michigan and comprising 160 dues-paying colleges, universities, and libraries throughout the US. HTRC was initiated in 2011 with a grant award from HathiTrust to the University of Illinois Urbana-Champaign (UIUC) and Indiana University. In 2019, the partnership was restructured slightly, with IU taking on the role of lead institution in the partnership.

HTRC has enabled unprecedented and interesting research in the humanities ranging from analyses of Hoosier native son Kurt Vonnegut's oeuvre to the analysis of the experience of Black women in the nineteenth century US. The latter example illustrates the power of HTRC and the "data capsule" approach for exploring the experience of a group of people who were not allowed to read or write, as was done by Nicole M. Brown in a pathbreaking analysis and explication of voices otherwise hidden.

RT - Research Technologies. "One of these things is not like the others," and RT is the odd center out, with more operational responsibility and funding related to service to IU than the rest of IU PTI.

RT services include designing and implementing supercomputers used by IU and the national research community, including:

- the first university-owned 1 TeraFLOPS supercomputer in the US (2001)
- the first distributed Linux cluster to achieve more than 1 TeraFLOPS on the LINPAC benchmark program (2003), made possible by the NSF-funded AVIDD award
- the first university-owned 1 PetaFLOPS supercomputer in the US (2013)

- the first NSF-funded cloud system for general research use for the national research community: Jetstream, funded in 2015 and put into operation in 2016.

RT has also collaborated with faculty of the Luddy School and its predecessors, and has won a total of four different "Challenge" awards at the IEEE/ACM SCxy conference.

RT has been a leader in advanced storage systems, operating one or more local storage systems based on the high performance Lustre system since 2005, while also staying involved in national and international leadership of the Lustre file system project. RT's leadership in storage extends back even farther than that, as IU was one of the first universities to install a major tape storage system operated with the very secure High Performance Storage System (HPSS). IU, in fact, wrote code that enabled two different tape storage systems to "mirror" each other and was the first university in the world to use this method, with a system in Indianapolis mirroring the one in Bloomington to provide the best possible data security. IU's official digital archive, IU ScholarWorks, depends on RT's tape storage system for its data storage.

In 2005, RT also led the way for IU to be the first US university to have alignment with HIPAA (the Health Information Portability and Accountability Act) as the "default" for all IU storage and computation systems. This means that IU's advanced cyberinfrastructure can be used to analyze and understand identifiable patient data. Very few universities provide this as a general capability even today, and IU biomedical research has been greatly enhanced and accelerated as a result.

Additionally, RT has been a leader and innovator in terms of developing and delivering visualization services. The RT Advanced Visualization Lab (AVL) promotes and supports the innovative application of visual technologies to enhance IU's research, education, creative activity, and community outreach missions. The majority of AVL technologies are installed in accessible campus spaces, such as lobbies, workspaces, and Student Technology Centers (STCs); additional and more experimental technologies are accessible in centrally located AVL spaces including labs at IU Bloomington and IUPUI. The AVL also provides expert consulting services, training opportunities, and learning resources related to visualization.

AVL distributed systems include:

- Large-format, ultra-resolution displays for visualization and collaboration (IQ-Walls). These systems, developed and designed by staff of the AVL, offer modestly-priced and extremely high-resolution display facilities.
- Virtual reality classrooms and laboratories for teaching and individual exploration
- A suite of cutting-edge VR and AR technologies, including the PIPES (Programmable Immersive Peripheral Environmental System) mixed reality interface system
- A spherical display developed by NOAA (Science on a Sphere) for presenting scientific and informational visualizations, and creating dynamic visual experiences
- 65-inch multi-touch monitors (IQ Tables) that can be reconfigured into table, drafting table, or landscape mode for exhibitions and multi-user engagement

RT has been a leader in software, as well. RT offers programming assistance and very often dedicates staff to support particular major research projects, including two of IU's three "Grand Challenge" projects. RT also contributes storage and computational resources to these challenges.

While the other IU PTI centers largely function as traditional R&D labs, RT's difference lies in its size, its base of university funding and its commitment to providing services to the IU community. Because RT has always had a headcount far greater than that of the other IU PTI centers and labs combined, and for that reason, care has been taken to ensure that RT does not exert too much influence over IU PTI's direction. At the same time, there have been moments when IU PTI's (or PTL's) future hung by a thread

and RT budgets and personnel were critical to its survival. Similarly, the most productive phase of IU PTI's history (when the number of grants, funding totals, and national influence were at their highest) have been during peaks in collaboration between RT and Luddy School faculty. IU PTI's emergence as a national power in cyberinfrastructure and RT's national prominence depend upon intellectual contributions of Luddy faculty and other staff affiliated with PTI. For example, RT now has an entire management group that develops and supports software for management of data from high-output instruments. These software environments were modelled after and based on concepts originally developed by CIRC under director Marlon Pierce's.

Office of the Executive Director and its predecessors. The IU PTI Executive Directors, and prior Science Directors, have always engaged in a research program of their own specification and usually with extramural funding gotten by these leaders. The founding Science Director Dennis Gannon was foundational in establishing PTL and IU as leaders in high performance computing and grid computing, and was personally a lynchpin in PTL and RT's early success in becoming part of the NSF-funded TeraGrid (described below). As Science Director, Beth Plale put a great deal of focus on data-centric computing and led the creation of one of the most crucial reports ever produced by IU PTI – the final report about PTL and PTI activities submitted to the Lilly endowment at the end of the Lilly grant that created PTI in 2014. Professor Plale was also instrumental in shaping the governance structure and among PTI center leaders. The Office of the Executive Director was created as a distinct group in 2017 after a cancer diagnosis resulted in splitting Stewart's responsibilities three ways: Matthew R. Link became acting AVP of Research Technologies, David Y. Hancock became acting Principal Investigator for Jetstream, and Von Welch took over temporarily as acting Executive Director of PTI. The new roles for Link and Hancock soon became permanent, and, as his health improved, Stewart relieved Welch and resumed responsibility as Executive Director.

The Office of the Executive Director now leads the following activities in three major projects and one operational group:

- XSEDE. The Office of the Executive Director is responsible for overall management of IU's subcontract for XSEDE – the eXtreme Science and Engineering Discovery Environment.
- Return on investment in cyberinfrastructure. Stewart has carved a niche in US cyberinfrastructure research related to analysis of return on investment in cyberinfrastructure and in facilitation of adoption of cloud technologies. He and his colleagues lead several related projects all designed to quantitatively and qualitatively assess the return to academic institutions on investment in cyberinfrastructure. IU PTI is now the leading producer of peer-reviewed reports on ROI analyses of cyberinfrastructure investments in the US.
- Humans Advancing Research in the Cloud. This project looks at obstacles to adoption of cloud computing in research and seeks to find ways to overcome these obstacles.
- Cyberinfrastructure Assessment and Evaluation. The CAE group is led by Julie Wernert and includes 3 FTEs, all of whom are involved in assessment of cyberinfrastructure locally at IU and nationally through XSEDE, and several other grant-funded projects at IU and at other institutions. CAE also manages assessment of multiple national and international conferences. Assessment is becoming a critical aspect of all grant-funded projects, and CAE supports itself almost entirely on grant subcontracts.

Labs currently being incubated. Right now, there are two labs that are being "incubated" with an intention to graduate to center status. They were both created in 2019, PTI's 20th year, and are being incubated under the wings of existing centers:

- **eLearning Research and Practice Lab.** Now housed within the D2I center, the eLearning Research and Practice Lab is a link between IU faculty researchers and the systems that store eLearning records, helping to enable systematic and sustained research. The lab leads advances in

understanding of students' eLearning behaviors, performance, and outcomes, and their associated social contexts, through cutting-edge research that addresses practical and theoretical questions at the intersection of learning, education, and technology. Its research is collaborative, empowering faculty affiliates to examine student eLearning rigorously and responsibly, and to contribute their insights and expertise to an interdisciplinary research community. Through this work, the lab develops evidence-based practices, interventions, and tools to advance student learning at IU and beyond.

- **Crisis Technology Innovation Lab – CTIL**. The Crisis Technologies Innovation Lab (CTIL) is a collaboration between the Luddy School of Informatics, Computing, and Engineering and University Information Technology Services (UITS) to accelerate research and practice on the use of next generation technologies in the front lines of emergency and crisis response. CTIL is affiliated with CIRC. The last decade has seen dramatic growth of technologies that impact society, from data science and machine learning to pervasive devices, social media, and drones. This same decade has also brought major challenges and threats to human well-being and the economy, including increased severity and frequency of natural disasters, dependency on a fragile technology infrastructure, and demand on first responders. CTIL explores the urgent need for new approaches to using technology to manage crises that are reliable, scalable, and affordable; that can interoperate between emergency professionals and the public; and that can help save lives in a complex, challenging environment.

7.2. Labs and centers that were merged or decommissioned

ANML – Advanced Network Management Lab. ANML was PTL's first lab, and its genesis was IU's leadership deploying and operating[33] the world's most advanced research and education network backbones, including the Internet2 network. ANML combined advances of the IU Global NOC with translational research in network management, cyber-threat detection, advanced application-based routing, network traffic characterization, and advanced network protocols, to improve our ability to understand and securely use advanced networks. Some of ANML's more exciting and notable accomplishments include the following:

- ANML cyber-threat detection activities led to an agreement with the US Air Force to assist the Federal government in understanding emerging internationally-scoped DDoS activity. ANML assisted in the deployment of DDoS threat detection instrumentation across networks that provide inter-country network traffic.
- Tsunami, a high-speed bulk data transfer protocol that's resilient to network impairments. Tsunami was further developed by Metsähovi Radio Observatory, Finland's only astronomical radio observatory, and used to transfer vLBI radio astronomy data.
- ANML's most widely-used contribution is the secure file transfer system Slashtmp. Slashtmp allows users to transfer large files quickly and securely. IU has licensed Slashtmp to several other universities, and itself continues to use Slashtmp to transfer sensitive information safely. Slashtmp has been in service for over 18 years and is used for data transfer, including critical and protected health information.

SDAL – Scientific Data Analysis Lab. The Scientific Data Analysis Lab was the last PTL lab formed and, sadly, the first one disbanded. Led by Randy Heiland, SDAL had a straightforward mission: enhance the effectiveness of researchers at IU by offering scientific data analysis and depiction services. It was an important mission, and SDAL produced excellent work. SDAL also did significant work on behalf of nonprofit organizations in the greater Indianapolis area. SDAL's business model plan was to fund itself through obtaining subcontracts on grants to other IU PIs. While this model might have been successful at IU today, it did not work during SDAL's activity, from 2003-2007.

[33] Haskett, James A., "A History of Academic Computing at Indiana University Bloomington 1940-2000", Bloomington Academic Computing Services, Indiana University, 1986. http://hdl.handle.net/2022/14618.

KAPLab – Knowledge Analysis and Projection Lab. Some of the Pervasive Technology Labs focused on developing core technologies; others concentrate on targeted, in-depth application and integration of core technologies to address important real-world needs. The Knowledge Acquisition and Projection Lab, the first externally-funded lab affiliated with PTL, was initially charged with developing more efficient electronic warfare maintenance systems for the United States Navy. The objectives were to reduce costs, increase system up-time, and improve military readiness. Working with a research consortium that included IU, the Naval Surface Warfare Center, Crane Division, and Purdue University, the lab developed a knowledge management system to provide dynamic user and situation-aware support for diagnosis and repair processes. The system adapted to ship particulars and to users with varied levels of training and expertise. As a part of an international research collaboration spanning the US, Australia, New Zealand, and the UK, the lab was also active in developing wide area data acquisition and instrument control protocols (the CIMA project) based on semantic web technologies. The result was a system that could describe an instrument completely with respect to measurements so that a remote user or computer could, with proper authorization, access and control an instrument without additional information. These technologies were used in ecological sensing networks, beamline experiments at the Advanced Photon Source at Argonne National Laboratory, remote astronomy applications and in laboratory instrument management and control. The KAPLab was active from 2001 to 2008 as part of both PTL and IU PTI, and was decommissioned when the Director, Dr. Rick McMullen, left Indiana University.

VIS – Visualization and Interactive Spaces Lab. VIS leader Pauline Baker was already an international celebrity when she arrived at IU from the University of Illinois Urbana-Champaign, with a textbook on computer graphics that had been translated into over 20 languages. While at IU, the VIS Lab and Professor Baker innovated in the field of augmented reality, which combines intuitive physical interaction with advanced (and often stereoscopic) visualization in scientific and educational contexts. The VIS Lab was active from 2002 to 2011 and closed as Dr. Baker prepared for retirement.

CREST – Center for Research in Extreme Scale Technologies. CREST was, in some ways, one of IU PTI's most successful centers, holding the record within IU PTI for the largest amount of grant dollars brought in for software research & development in a single year. CREST grew out of the combination of the Open Systems Lab, led at IU by Professor Andrew Lumsdaine starting in 2001, combined with the research of Thomas Sterling who moved to IU in 2011. The idea behind CREST was to combine Lumsdaine's work "from the top down" in building high performance parallel computing libraries with Sterling's work "from the bottom up" in building advanced runtime systems. CREST had a real shot at revolutionizing exascale computing in the US. CREST and its predecessor OSL created the majority of patents granted to investigators affiliated with IU PTI. CREST's end came about in 2018 through the failure of the US exascale initiative to experiment in the area of exascale runtime systems, but the center's impact lives on in the research programs of its affiliated faculty: Thomas Sterling, still at IU and at work developing new processors for exascale computer systems; Andrew Lumsdaine, now at the University of Washington; Ryan Newton, now a group leader at Facebook; Jeremy Siek, one of the intellectual leaders in formal methods in computer science at IU; and Martin Swany, formerly affiliated with CREST and now affiliated with D2I.

7.3. Center activities in IU PTI's 21st year

Below are highlights of new activities and accomplishments for individual IU PTI centers between IU PTI's 20th anniversary on September 22, 2019 and the end of Fiscal Year 2020 (June 2020).

CACR – the Center for Applied Cyberinfrastructure Research.

- CACR launched a service called SecureMyResearch, which provides researchers with consulting and resources to help them protect research data and comply with cybersecurity requirements in grants, contracts, and data use agreements. The service aims to reduce the cybersecurity and compliance burden, helping IU researchers do the world-class research they do best.
- CACR and the IU-led OmniSOC are working together to implement and test new AI software designed to aid in the detection of cybersecurity threats within network traffic.
- CACR's ongoing leadership in protecting the cybersecurity of more than $7B in NSF-funded research was confirmed with a $12.5M grant extension for the NSF Cybersecurity Center of Excellence (Trusted CI) for expansion of its activities.
- CACR's team of experts helped prepare election officials in all 92 Indiana counties for cybersecurity incidents related to the 2020 general election and beyond.
- CACR onboarded its first client, the National Radio Astronomy Observatory. In a first for IU, network data from an NSF facility is now being monitored by IU's OmniSOC, a ResearchSOC partner.
- Through Trusted CI and ResearchSOC, CACR's leadership showed through at PEARC19, July 28–August 1, where CACR staff and collaborators received the PEARC19 *Phil Andrews Award for Most Transformative Contribution* for SWIP's publication, "Integrity Protection for Scientific Workflow Data: Motivation and Initial Experiences" and presented the paper Trusted CI presented the paper "Trusted CI Experiences in Cybersecurity and Service to Open Science."
- The CACR Principles-based Assessment for Cybersecurity Toolkit (PACT) team delivered their final assessment report in their engagement with Scripps Institution of Oceanography (SIO) and UC San Diego.
- CACR staff shared their cybersecurity expertise and experience in developing a center of excellence with the $3M Cyberinfrastructure Center of Excellence Pilot.
- Cybersecurity leadership and served as the CISO to The Open Science Grid (OSG), Institute for Research and Innovation in Software for High Energy Physics (IRIS-HEP), and SWAMP (Software Assurance Marketplace) projects.

Cyberinfrastructure Integration Research Center - CIRC

- CIRC has been approved as an official RC center within OVPIT.
- The CIRC-supported SimCCS project for modeling carbon capture and sequestration scenarios was named an R&D100 award winner in two categories.[34]
- CIRC team members are developing a Web-based science gateway for both modelers and decision makers in the energy sector that provides access to modeling and simulation codes on high performance computers.
- CIRC is included in the NIH-funded IUSM Alzheimer's Disease Drug Discovery Center, led by Dr. Alan Palkowitz; Dr. Kun Huang leads the bioinformatics core area that includes CIRC. CIRC team members are working with multiple faculty members in the IU School of Medicine and the IUPUI Bioinformatics Department to develop science gateways to provide software as a service, and in the larger effort to design a comprehensive data management plan for the project.
- CIRC team members are part of the NASA-funded "Quantifying Uncertainty and Kinematics of Earthquake Systems (QUAKES)" project, led by long-term collaborator Dr. Andrea Donnellan of NASA JPL.
- CIRC team members led thirteen peer-reviewed efforts at PEARC20: seven presentations, two birds-of-a-feather sessions, three posters, and one tutorial.

[34] https://www.lanl.gov/discover/news-release-archive/2019/November/1106-rd-100-awards.php

- The graduate level computer science special topics course, "Applied Distributed Systems," co-instructed by CIRC's Marlon Pierce and Suresh Marru, had its highest enrollment (57) since it began in 2016.

Data to Insight Center - D2I

- This spring, D2I Director Beth Plale was named the inaugural Michael A. McRobbie and Laurie Burns McRobbie Bicentennial Professor in Computer Engineering. This endowed professorship will enable Plale to explore her research interests with funding support from the endowment associated with this professorship.
- D2I leadership published a roadmap for D2I research and development activities for the next three to five years.

Hathi Trust Research Center - HTRC

- Local support expanded! IU PTI has funded an additional staff member to work in HTRC and increase knowledge of and support use of HTRC services within the IU humanities community.
- The HathiTrust Digital Library research corpus has been expanded to more than 17 million volumes.
- HTRC released Extracted Features 2.0, a derived dataset consisting of metadata and data elements extracted from volumes in the HathiTrust Digital Library. The dataset is composed of 17+ million JSON files representing a snapshot of the HathiTrust corpus from February 2020.[35]
- Glen Worthey joined the HathiTrust Research Center as Associate Director of Research Support Services (based at University of Illinois). Worthey comes to HTC from Stanford, where he was the digital humanities librarian and founding head of Stanford's Center for Interdisciplinary Digital Research.

National Center for Genome Analysis Support - NCGAS

- NCGAS has a new director, Dr. Sheri Sanders, and a new suite of collaborations with the Luddy School of Informatics, Computing, and Engineering and the IU Bloomington Department of Biology.
- This spring, NCGAS launched an all virtual class on Introduction to R for bioinformatics that was attended by more than 300 students.

Research Technologies - RT

- On the day of Indiana University's 200th anniversary – 20 January 2020 – the new Big Red 200 supercomputer was dedicated by IU's 18th President Michael A. McRobbie at IU's Bicentennial event. With a processing capability of nearly 10 PetaBytes, Big Red 200 is full of GPUs and its configuration is optimized to support use of AI in research and development of new AI tools.
- Also on "IU Day," 20 January 2020, the Office of the VP for Information Technologies unveiled a high-resolution Crystal Wall in the Cyberinfrastructure Building's Wrubel Commons. Implemented and programmed by Research Technologies and other OVPIT colleagues, this device is one of the largest curved, mobile Crystal Light Emitting Diode (CLED) displays in the US. With a resolution above 4K, this display highlights scientific, data, and artistic visualizations with stunning clarity and brightness. Nearly 28 feet wide and 10 feet tall, with 108 panels, it enables HPC interaction, video conferencing, and stereoscopic 3D and spatial tracking for virtual reality applications.
- A new supercomputer called Big Red 3 has been put into service to support large-scale CPU-based calculations.
- Recent imaging of the event horizon of the M87 black hole was enabled by the Event Horizon Telescope (a telescope array consisting of a global network of radio telescopes), a large number

[35] See https://wiki.htrc.illinois.edu/pages/viewpage.action?pageId=79069329

of scientists, NASA spacecraft, and a variety of computing resources with an increasing portion being done on cloud resources, particularly Jetstream.

- In October, RT hosted two conferences in the same week: the High Performance Storage System (HPSS) User Forum, or HUF19, and the Campus Alliance for Advanced Visualization, or CAAV. As IU PTI EOT Manager Robert Ping stated, "Hosting these conferences fits into IU's strategic plan relating to outreach and education. UITS and the Pervasive Technology Institute at IU have become known for bringing user communities together in order to take advantage of expertise and training, share ideas to accelerate IU's supercomputing prowess, and network with folks in the field to stay abreast of current topics."

Office of the Executive Director

- The Humans Advancing Research in the Cloud (HARC) project completed its first phase with publication of work resulting from the Cloud Research Support Engineers (CRSE) Phase-1 effort, which culminated in a workshop held at PEARC19 at the end of July. All work, papers, and presentations were uploaded to the HARC GitHub site.[36] Fall 2019 saw the project examining alternative pathways forward. Voss was invited to participate in a 2-day workshop sponsored by Microsoft for Latin American research universities, presenting a discussion of research in the US, its directions toward use of commercial cloud cyberinfrastructure, and the HARC project experiences to date. HARC project members also participated in a workshop at Internet2's TechEx conference in New Orleans in December updating attendees on our findings as well as the experiences of three of our CRSEs. HARC's second phase took on a traditional sub-grant award model, and selected four (4) for funding - Arizona State University, Georgia State University, University of Pittsburgh, and University of Notre Dame.[37] HARC continues, with the support of CRSE2 participants, to advance the content and structure of the GitHub community resource, seeking specifically to increase the number of useful cloud tools (reusable code) for various vendors, as well as sharing of experiences and other related useful documentation. For the HARC workshop at PEARC20, a call for participation resulted in five papers submitted, a number of invited presentations, and a full day workshop.[38] The workshop was a joint effort with partners at the National Institutes of Health Science and Technology Research Infrastructure for Discover, Experimentation, and Sustainability (STRIDES).[39]
- IU PTI has continued publication of groundbreaking research related to analysis of return on investment in cyberinfrastructure. We completed an analysis of ROI for federal investment in XSEDE - the national advanced CI organization formally known as the "eXtreme Science and Engineering Discovery Environment." We also completed a pathbreaking new analysis of the opinions of IU Principal Investigators on the importance of IU's advanced cyberinfrastructure to their success in obtaining extramural funding. The answer, in sum, very important.

8. Conclusion and a look forward

The Indiana University Pervasive Technology Institute began as an idea by then-VP Michael A. McRobbie, backed by Indiana University's innovative spirit and an initial $30M investment from the Lilly Endowment, Inc. IU PTI has matured over nearly twenty years as part of a university-wide effort to achieve a goal set in 1997 by Myles Brand, the 14th President of Indiana University, to make the institution "a leader [among institutions of higher education], in absolute terms, in the use and application

[36] https://github.com/HARC-PTI

[37] https://itnews.iu.edu/articles/2020/HARC-project-announces-four-awards-.php

[38] https://harc.iu.edu/workshops/pearc20-conference.html

[39] https://datascience.nih.gov/strides

of information technology."[40] This goal seemed all but impossible at the time it was first articulated. At present, Indiana University can justifiably claim leadership in this arena.

In 2008, in his letter submitting IU's proposal for second-round funding, IU President Michael A. McRobbie committed that at the end of the funding then requested then to create the current structure of IU, IU would maintain IU PTI primarily on the basis of external grants and contracts. President McRobbie also wrote that in 50 years we might look back and see the creation of IU PTI as one of the critical turning points in the development of high-tech research at Indiana University. 20 years on, IU PTI can certainly claim an important role in the evolution of Indiana University as a high-tech university.

IU's ambition persists today as part of 18th President Michael McRobbie's goal for Indiana University to be one of the great universities of the 21st century. IU PTI has been a major contributor to achievement of these major goals by two of IU's truly great presidents: Myles Brand and Michael. A. McRobbie. IU PTI is regarded as one of the top advanced computing R&D centers in academia, it has done more than just be sustained. It has thrived and served Indiana University, the state of Indiana, the United States, and the global community in the process. IU PTI has been extremely successful for two decades and remains well positioned for continued success in the coming decades.

9. Acknowledgments

Thanks must go first and foremost to the students, hourly staff, professional staff, postdoctoral fellows, and faculty who have been a part of PTL and IU PTI over the past 20+ years. While all of the financial, organizational, and leadership support provided to IU PTI by Indiana University and the Lilly Endowment have created the opportunities for IU PTI to excel, it is the people of IU PTI who achieved the goal of excellence in research and innovation.

This document has benefitted from the intellectual contributions of many people involved in IU PTI past and present, including particularly:

- IU President Michael A. McRobbie, who was the Principal Investigator on the two proposals to the Lilly Endowment that created the Pervasive Technology Institute
- IU Luddy School of Informatics, Computing, and Engineering leaders: Founding Dean Michael Dunn, Executive Associate Dean Erik Stolterman, Associate Dean for Research Kay Connelly.
- Professor Dennis Gannon, the original Science Director of the Pervasive Technology Labs
- Dr. D.F. "Rick" McMullen, who developed the first version of the "bubble diagram" in Figure 1-5

IU PTI has benefitted from many federal grants, as well as private grants and contracts. Major funding for IU PTI (awards greater than $4M) has come from the following sources:

Fiscal Year Awarded	Project Title	IU PTI Center	Sponsor Name	Total Amount
2005	TeraGrid Resource Partners	RT	University of Illinois, Urbana-Champaign	$9,186,642
2010	FutureGrid: An Experimental, High-Performance Grid Test-bed	DSC	NSF	$10,133,500
2012	XSEDE: eXtreme Science and Engineering Discovery Environment	RT	University of Illinois, Urbana-Champaign	$6,315,115
2012	The Open Science Grid The Next Five Years: Distributed High Throughput Computing for the	RT	University of Wisconsin	$5,097,620

[40] Dunn, J. Michael, & McRobbie, Michael. (1998). *Information technology strategic plan: architecture for the 21st century*. Indiana University. http://hdl.handle.net/2022/471

	Nations Scientists, Researchers, Educators, and Students			
2013	Center for Trustworthy Scientific Cyberinfrastructure	CACR	NSF	$4,518,845
2014	High Performance Computing System Acquisition: Jetstream - a self-provisioned, scalable science and engineering cloud environment	RT	NSF	$13,799,929
2016	CICI: Center of Excellence: Center for Trustworthy Scientific Cyberinfrastructure	CACR	NSF	$7,829,993
2017	XSEDE 2.0 Extreme Science and Engineering Discovery Environment	RT	University of Illinois, Urbana-Champaign	$6,461,391
2018	CICI: CSRC: Research SOC	CACR	NSF	$4,933,641
2020 - in our 21st year	Category I: Jetstream 2: Accelerating Science and Engineering On-Demand	RT/CIRC/CACR/PTI	NSF	$11,999,999

Table 5-1. Major funding awards to IU PTI ($4M and higher).

An organization that persists for 20 years does so as the result of the efforts of many people. Craig Stewart, Executive Director, would particularly like to thank the following people:

- IU President Michael A. McRobbie and IU Vice President Bradley C. Wheeler. President McRobbie's vision and support throughout 20+ years, and for Vice President Wheeler's oversight and support of IU PTI for 15 of its 20 years sustained the organization. Without these two individuals, IU PTI would not be what it is today
- Therese Miller and Daphne Siefert. Therese and Daphne were the heart and soul of Pervasive Technology Labs; there were times when PTL would have collapsed had either one of them wavered in their commitment to success for even a millisecond. Therese has been responsible for the successful management of the completion of more funded grant proposals to PTL and IU PTI than any other person, and deserves more credit than any other single person.
- Beth Plale. The inaugural Michael A. McRobbie and Laurie Burns McRobbie Professor in Computer Engineering rose to national and international prominence as a scientist concurrently as she emerged as a leader within PTL and PTI. Her leadership and influence are largely responsible for IU PTI's accomplishments and the maturity of its governance models.
- In addition to Beth Plale, Stewart would like to offer special thanks to the following faculty and administrators at IU, who have been critical to IU PTI's Success: Thomas Sterling, Ryan Newton, Martin Swany, Randy Bramley, Dennis Gannon, David Wild, Katy Boerner, Kay Connelly, Dennis Groth (Luddy School of Informatics, Computing, and Engineering); Sarita Soni, Jeff Zalesky, Rick Van Kooten, Fred Cate, Lauren Robel (IU and IU Bloomington Administration); Matt Hahn, Peter Cherbas, Nicole Jacquard, Ben Motz, Caty Pilachowski, Ted Castronova (College of Arts and Sciences); Ora Pescovitz, Tatiaina Foroud, Andy Saykin (IU School of Medicine).
- In memory of: Vern Maxson, Dick Repasky, Gerry Bernbom, and Christopher S. Peebles. They hold a special place in the heart of everyone who worked with them.
- In memory of, and with special thanks to, Myles Brand, IU's 14th President. It was his vision that led to the creation of IU PTI. Stewart corresponded with former President Brand when it was clear that Brand's pancreatic cancer was unstoppable, telling President Brand of the 2nd round of funding for IU PTI and its move into the Innovation Center building. President Brand replied that he was gratified and proud of IU PTI's success.
- Von Welch. As Associate Director and Director of CACR, Von was critical to the growth of CACR and IU PTI as a whole. Welch was also Stewart's most thoughtful discussion partner and constructive critic in the development of a core mission, mode of operations, and governance

structure for IU PTI. Welch has also spent more time as acting Executive Director of IU PTI than any other person, in particular while Stewart was being treated for cancer. Stewart's long-term goal was to have an answer to the question "Why should PTI exist" that Von found acceptable. That goal was achieved this year.

- Eric Wernert, Matt Link, David Y. Hancock, Stephen Simms, Mary Papakhian, Robert Henschel, George Turner, Rich Knepper, Richard Meraz. These senior leaders of Research Technologies were the brain trust behind RT's success while Stewart also held the role of Associate Dean for RT, and the people who enabled RT to be innovative and successful at the national and international levels. Wernert deserves special note as the holder of the record for greatest longevity as one of Stewart's professional colleagues and a person who enabled advanced visualization to be an innovative success at IU. Hancock deserves special note as the PI of Jetstream2, the next step in the evolution of the idea that we all had years ago and which turned into the Jetstream system.
- Marlon Pierce, Rob Quick, Marie Ma, and Tom Doak, who as staff members (or non-tenured faculty) contributed essentially to the success of core elements of IU PTI-affiliated centers.
- Malinda Husk, the first of the full-time editors helping PTL and IU PTI's grant and publication success. Stewart's earliest grant proposals were funded in large part thanks to Husk's editing expertise.
- Robert Ping, the stalwart and effective leader of IU PTI's outreach programs.
- Winona Snapp-Childs, manager of the Collaboration, Engagement, and Support group. The emergence of Dr. Snapp-Childs as an expert in grant proposal preparation and leader of the group responsible for pre-award support and post-award outreach was critical to the maturation of IU PTI's success and its continuity in recent years.
- Special thanks to Harmony Jankowski, the last editor with whom Stewart gets to work at Indiana University, and one of the very best.
- Rudeana Honeycutt and Monica Shannon, Stewart's two long standing administrative assistants, who have kept Craig from driving himself and those around him nuts more than once.
- Craig Stewart's family: wife Marion Krefeldt, children Kai (George) and Tony (Kristen), and grandchildren Michael, Katja, Elan, and Madeline.

10. Appendix 1: IU PTI Timeline and Background

A more detailed timeline of major accomplishments by IU PTI and its predecessors, along with IU PTI's major successes, is available online at pti.iu.edu/about/timeline.

Year	Event
1999	● Indiana Pervasive Computing Research Initiative (IPCRES) received a $30M award from the Lilly Endowment. $15M was used to fund the initial phases of growth of what was then called simply the School of Informatics. $15M was used to start the Pervasive Technology Labs. Dennis Gannon was appointed Science Director.
1999-2005	● The Pervasive Technology Labs, as IU PTI was then called, focused on recruiting top faculty talent to what was then called simply the School of Informatics (now called the Luddy School of Informatics, Computing, and Engineering).
2001	● Stephen Wallace, already a professional staff member at Indiana University, was appointed as Director of the Advanced Network Management Lab. ● Geoffrey C. Fox was recruited to Indiana University as Professor in School of Informatics and Director of the Digital Science Center. ● Andrew Lumsdaine was recruited to Indiana University as Associate Professor in School of Informatics and Associate Director of the Open Systems Lab, the first lab in PTL. ● Brian Voss was appointed Chief Operating Officer of PTL, in addition to his existing responsibilities as Associate Vice President of Telecommunications in UITS/OVPIT.
2001	● Independent of PTL, The Center for Applied Cybersecurity Research was created by then-VP Michael A. McRobbie and headed up by founding Director Fred Cate, Professor of Law
2002	● Pauline Baker was recruited to Indiana University as Professor in School of Informatics and Director of the VIS (Visualization and Interactive Spaces) Lab. ● D.F. "Rick" McMullen, already a professional staff member at Indiana University, was appointed as Director of the Knowledge Acquisition and Projection Lab.
2003	● Randy Heiland was recruited to Indiana University as Associate Director of Scientific Data Analysis Lab (SDAL).
2005	● Craig Stewart became Chief Operating Officer of PTL and Associate Dean of Research Technologies.
2007	● Scientific Data Analysis Lab (SDAL) closed.
2008	● With a second round of funding from the Lilly Endowment, PTL was restructured into the Pervasive Technology Institute, with Craig Stewart as Executive Director of IU PTI as well as Associate Dean for Research Technologies. IU PTI included three centers as of 2008: o The Digital Science Center evolved out of the lab previously run by Director Fox. o The Data to Insight Center was established as a center of IU PTI by elevating the lab run by Dr. Beth Plale to center status. o CACR became affiliated with IU PTI with Fred Cate as its Director. ANML was incorporated into CACR. ● Beth Plale was appointed as Science Director of IU PTI. ● Dennis Gannon, who had been the Science Director of PTL, retired from Indiana University. ● The structure of IU PTI was expanded to include Research Technologies as one its centers. Collaborations between Research Technologies and IU PTI research centers were pursued vigorously and encouraged. ● IU PTI put new focus on fostering collaborations between faculty-led IU PTI centers and the Research Technologies Division of UITS (largely successfully). ● KAPL (Knowledge Acquisition and Projection Lab) closes.
2009	● FutureGrid was awarded $10.1M from NSF to Indiana University (Geoffrey C. Fox, PI). This grant award created FutureGrid, a distributed testbed for grid and cloud computing, greatly aided by the Research Technologies Division of UITS. This is one of just a handful of federal awards to Indiana University, Bloomington for an award total amount in excess of $10M as of the writing of this report.
2011	● Thomas Sterling was recruited to Indiana University and the Center for Research in Extreme Scale Technologies was created, under the leadership of Director Andrew Lumsdaine and Associate Director and Chief Scientist Thomas Sterling. ● VIS (Visualization and Interactive Spaces) Lab closed as Director Pauline Baker retired from Indiana University.
2008-2014	● The majority (albeit not all) of the biggest and most intellectually important research done by IU PTI from 2008 to 2014 involved researchers depending on and leveraging cyberinfrastructure and services provided and supported by the Research Technologies Division of UITS.
2014	● The second grant award from the Lilly Endowment ended and the final report was published. ● The Center for Research in Extreme Scale Technologies (CREST) ended its relationship with IU PTI.

	● Von Welch was promoted to Director of CACR following Dr. Fred Cate's promotion to Indiana University VP for Research. ● Jetstream grant award totaling $14,496,404 from the National Science Foundation to Indiana University with Craig Stewart as PI. This award created the Jetstream cloud system, now regarded as one of the most-liked cyberinfrastructure resources funded by the NSF. Jetstream is led by IU PTI, and since February of 2017, has been led by PI and Director of Advanced Cyberinfrastructure David Y. Hancock. With this award, IU PTI became responsible for two of the six total federal grant awards in excess of $10M to Indiana University, Bloomington from 1999 to the time of this report.
2016	● Thomas Sterling becomes Director of CREST.
2017	● Leadership of Research Technologies and IU PTI split into two positions, with Matt Link becoming the Associate Vice President for Research Technologies and Craig Stewart moving forward as Executive Director, Pervasive Technology Institute. David Hancock assumed the title and role of PI of Jetstream. ● Data to Insight Center Director Beth Plale accepted an appointment at NSF for three years under the Intergovernmental Personnel Act (IPA).
2018	● CREST is disbanded, although one important theme of its research continues on under the leadership of Professor Thomas Sterling in his lab in the Luddy School of Informatics, Computing, and Engineering. ● IU PTI centers begin jointly funding central supporting activities and personnel. The first such appointment is a new editor to better support IU PTI competitiveness in pursuing grant awards. ● IU PTI adopts a shared governance model and center directors are given the title Associate Director, IU PTI. ● HTRC openly advertised as a standalone IU PTI center in wake of re-funding of HTRC by the HathiTrust/University of Michigan, with John Walsh (SICE/ILS) as director and PI.
2019	● IU PTI's first privately funded project with a budget of over $1M begins in earnest – Humans Advancing Research in the Cloud (HARC). ● Cloudseal, a startup initiated by CREST Associate Director Ryan Newton, is purchased by Facebook. ● IU PTI funds technical expert to increase support for preparation of grant proposals. ● eLearning Research and Practice Lab created and affiliated with IU PTI. ● Crisis Technologies Innovation Lab created and affiliated with IU PTI. ● Von Welch appointed executive director for cybersecurity innovation at Indiana University.
2020	● Jetstream2 grant award totaling an initial $11,999,999 to create a much bigger successor to the initial Jetstream system, with particular capabilities for AI. The Jetstream2 award is anticipated to be for a total of 10 years and an initial version and then a second "refresh" after 5 years. ● Craig Stewart retires as Executive Director of IU PTI October 1, 2020. Brian Voss named Interim Executive Director.

10.1. Relationship to the Research Technologies Division

Research Technologies is a division of UITS that provides advanced cyberinfrastructure services and systems for use by the Indiana University community, engages in enhancing education and the economy of Indiana, executes federally funded grant awards, and is affiliated with IU PTI. IU PTI collaborates with and, in ways, depends on Research Technologies, but is more focused on externally-funded research. Research Technologies' mission is driven first by Indiana University's needs, and meets those needs through use of Indiana University general funds. Thus, Research Technologies is somewhat buffered from the vagaries of federal funding actions. IU PTI, exclusive of Research Technologies, receives a small amount of its total funding from Indiana University. For this reason, the centers other than Research Technologies are more heavily influenced by what the federal government will fund than on alignment with Indiana University's needs, capacity, and expertise. However, the two organizations are somewhat interdependent. IU PTI is a source of grant monies that flow into Research Technologies, and Research Technologies provides much of the cyberinfrastructure that other affiliated centers and labs use as "homes" for their research projects. RT and the rest of PTI often collaborate very closely on large projects such as Jetstream and Jetstream2.

10.2. Relationship to OVPIT

IU PTI is unusual in that it reports to the CIO and Vice President for Research at Indiana University. Most of IU PTI's peers and would-be peers report either to a Vice President or Vice Provost for Research or are part of their universities' academic unit where the Department of Computer Science resides.

Factors contributing to IU PTI's close ties to OVPIT include the following:

- PTL and IU PTI began within OVPIT under the leadership of President McRobbie, who has issued strong directives regarding the importance of IU PTI's success. This history and OVPIT's dedication and fidelity to priorities set by President McRobbie account for the growth of IU PTI with its center of gravity and administrative reporting line being to the VP for Information Technology and CIO.
- In times of funding shortages, OVPIT was able to double down on its commitment to IU PTI. At these same times, facing particularly decreased enrollment income since 2016 as a result of fewer foreign students, the Luddy School was forced to scale back its direct involvement in funding elements of IU PTI.
- It makes sense in terms of Indiana University's strategies in computer science and cyberinfrastructure research, development, and delivery, which are based on the three-legged approach highlighted above.

IU PTI's close ties to OVPIT benefit OVPIT. The state authorization for creating the Cyberinfrastructure Building (CIB) specified that the debt service on the building be paid from F&A monies, and delivering such monies to OVPIT is one of the outputs of IU PTI's effectiveness. In a more intellectually interesting way, there is a mutually beneficial interplay between IU PTI RD&D efforts and Research Technologies service delivery. The collaboration between the Research Technologies Division of UITS and the rest of IU PTI helps identify the line between "interesting enough to fund through research grants" and "things in which we should invest our money." Thus, both Indiana University's research and investments are made more effective.

At the same time, IU PTI is inherently designed to be a flexible and collaborative organization. The success of IU's mission of research, education, and engagement in the life of the state, nation, and world should be what matters most to any subunit of IU and to any staff member or academic appointee of IU. One of the staff members within IU PTI used an old Arabic saying to describe the effect of IU PTI: "the good is in what happens." IU PTI has achieved a great deal of good over now twenty plus years. There is nothing magic about IU PTI reporting up within OVPIT; it could easily have its center of gravity and administrative reporting line up somewhere else within the university. What's important to the overall success of IU PTI and IU generally in the area of cyberinfrastructure and computer and computational science are these two factors:

- the "three-legged stool" structure of basic research (currently the Luddy School), excellent CI system implementation, delivery, and support (currently the Research Technologies Division of UITS), and applied R&D in between (IU PTI)
- a focus on benefitting IU, the State of Indiana, the US and the world

Names and reporting lines are, in the end, irrelevant. It is this triad of related foci and commitment to service that makes IU PTI's impact on the world through advanced computing special.

10.3. Relationship to the Luddy School of Informatics, Computing, and Engineering

The Pervasive Technology Institute and the Luddy School of Informatics, Computing, and Engineering have evolved concurrently. As is the natural order of things, the Luddy School of Informatics, Computing, and Engineering has grown very rapidly – much more rapidly than IU PTI itself. Still, the early growth of what is now the vibrant and well known Luddy School was fueled in large part by synergies between IU PTI and the school. A few examples include the following:

- Early and critical faculty hires into Luddy SICE were actually funded by PTL's budget, including:
  - Dr. Geoffrey C. Fox
  - Dr. Andrew Lumsdaine
  - Dr. Pauline Baker
  - Dr. Beth Plale
- IU PTI has played a critical role in the evolution of Luddy SICE:

- All of Luddy SICE's first three Distinguished Professors have some tie to IU PTI, and other critical faculty hires and promotion have benefitted from ties to IU PTI:
  - Dr. Geoffrey Fox, recruited to IU as a result of IU PTI funding, became Luddy SICE's first faculty member promoted to the rank of Distinguished Professor.
  - Dr. Katy Boerner, who received early funding as a PTL faculty fellow, became Luddy SICE's second faculty member promoted to the rank of Distinguished Professor.
  - Dr. Filippo Menczer, whose lab received funding through the second-round Lilly Endowment grant supporting the Pervasive Technology Institute, became Luddy SICE's third faculty member promoted to the rank of Distinguished Professor.
  - The hiring of eminent computer scientists and engineers Thomas Sterling and Martin Swany was a direct result of recruiting by IU PTI leaders.
  - The appointment of Dr. Beth Plale as the inaugural Michael A. McRobbie and Laurie Burns McRobbie Professor of Computer Engineering.
- IU PTI has played a critical role in Luddy SICE's grant success:
  - The only three 8-figure (> $10M) grant awards reported through IU as accomplishments of Luddy as an IU Responsibility Center are thanks to IU PTI:
    - FutureGrid, funded for a total of $10,133,500, was led by PI Geoffrey Fox and largely written by IU PTI Executive Director Craig Stewart.
    - The largest single grant award to a person with a faculty appointment in Luddy SICE in the history of that school is the NSF Jetstream Grant, with IU PTI Executive Director as founding PI, for a total of $13,799,929 to date.
    - What will eventually supersede Jetstream as the largest grant award involving a person with a Luddy SICE faculty affiliation, Jetstream2, with an initial budget of $11,999,999 but an expectation of total funding from the NSF to exceed $30M over the next 10 years.
  - IU PTI played a critical role in Luddy SICE's engagement in what has now been a decade plus of success of three NIH clinical and translational studies awards, led by the IU School of Medicine but with significant Luddy SICE involvement (and a total value to IU of > $75M).

11. Appendix 2: Diversity in the PTI workforce

President McRobbie has set a goal of having the IU community mirror the state of Indiana. What is demographic breakdown of the Indiana population? Since IU PTI is part of the tech sector of the US economy, what do its demographics look like? The statistics presented here are as of July 1, 2020.

	Indiana population as a whole[41]	**US tech sector employment**	
		Overall[42]	**Manager**[43]
Female	50.7%	20% to 26%	26%
Male	*49.3%*	80% to 74%	74%
Non-binary	No good statistics on individuals who identify as non-binary		

Table 1. Current gender ratios (sources in footnotes) for State of Indiana and for US technology sectors

	Overall full-time employees	**Managers**	**Center / Lab leadership**
Female	26% (36 total)	45% (10 total)	43% (3 total)
Male	74% (102 total)	55% (12 total)	57% (4 total)
Non-binary	No good statistics on individuals who identify as non-binary		

Table 2. Combined gender ratios within IU PTI-affiliated Centers and the PTI Executive Director's office

	Indiana population as a whole[44] (*note terminology choices are from source)*	**US tech sector employment**[45]
White, not Hispanic	*78%*	*49%*
Black or African American	*10%*	*1%*
Hispanic or Latino	*7%*	*4%*
Two or more races	*2%*	*3%*
Asian (Indian subcontinent to Far East)	*3%*	*39%*
Other race		*3%*
Native Hawaiian or Pacific Islander	*0.04%*	-
Every other group		*< 1%*

Table 3. Racial and ethnic statistics for State of Indiana and US technology sectors

Another point of reference is where IU PTI and its forerunners started – or at least where research computing and applied R&D were on October 1, 1996 – Craig Stewart's first day in the role of Senior Manager of what was called Research Computing Services (RSC). There are no good records or statistics before that time. The Center for Innovative Computer Applications (CICA), in some ways a predecessor to IU PTI, was at that time a completely separate organization. As of October 1, 1996, RSC comprised 24 people total: 20 Men, 4 women, all white, save 1 Asian woman. Every leader was a white man. CICA was 12 people total: 9 white men, 1 Asian man, 2 women. RSC and CICA combined consisted of 29 white men, 5 white women, 1 Asian man, 1 Asian woman. No women in any leadership positions.

Where are we today?

[41] https://www.states101.com/gender-ratios/indiana

[42] https://recruitinginnovation.com/blog/diversity-in-tech/ and https://www.dreamhost.com/blog/state-of-women-in-tech/

[43] https://www.statista.com/chart/4467/female-employees-at-tech-companies/

[44] https://www.census.gov/quickfacts/fact/table/monroecountyindiana,IN/PST045219

[45] https://recruitinginnovation.com/blog/diversity-in-tech/

Glancing at organizational charts and lists reveals that IU PTI generally does not achieve President McRobbie's goal of "looking like Indiana." Too few women (we're at 26%), too many white people, far too few Black and Hispanic people. On the other hand, IU PTI is doing somewhat well in some regards. Qualitatively, one can look at our situation as follows:

- On presence of women overall, we are not where we should be, but we're about as good as or a little better than the tech sector in the US in general. IU PTI has more women employed at the manager level than national averages for the US tech sector. This is still nowhere near parity, but it indicates that efforts to improve diversity over the years have had some impact.
- Of the management groups led by women, there are also a total of three that are majority women overall (as is Science Node, for which IU PTI is responsible for funding solicitation and management). The groups that are majority women are particularly good signs that IU PTI is making progress.
- On the dimension of LGBTQ+ individuals, IU PTI is doing well in having and supporting diversity (based simply on informal counts of people who are "out" regarding sexuality). Neither Craig Stewart nor Rick McMullen, the leaders of Research Computing Services and CICA as of 1 October 1996, know of a single person who was LGBTQ+ *and* out. (Bob Cole, CICA's first director, was gay and out in 1981. Tragically he died of AIDS in 1991. He was one of the first casualties of this terrible disease among the IU IT community.) It's clear that LGBTQ+ individuals do not get to work completely free of uncomfortable interactions, but in this area, IU PTI can say we have gone from no visible diversity to reasonable diversity and good to better-than-usual levels of workplace comfort in the last two dozen years.
- We do not do as well in terms of diversity at the senior leadership level. At the level of Directors of RT, it's 4 men and one woman. The same is true at the Lab Director level.
- PTI staff for the first time ever included Black staff members as of 2015. This is an area where the tech sector is woefully inadequate in support of diversity in general. IU PTI has gone from a complete absence of Black people to a representation that is at least consistent with the US tech sector.

In summary: IU PTI is way ahead of where it once was in representing and supporting diversity, but still far from mirroring the diversity of the population of the state of Indiana or the US as a whole.

12. Appendix 3: There are two valleys of death, not just one

Each week, new academic papers and software releases herald the creation of a new prototype for a piece of software or cyberinfrastructure service. Most of these tools fulfill interesting and innovative functions, but few ever enjoy a useful life extending beyond the publication of an academic paper or perhaps the depositing of the prototype's code in a code repository. The difficult path from *initial success as an idea* to *success as a widely used product* is often referred to as "the valley of death." Many ideas enter; few survive the climb up the other side.

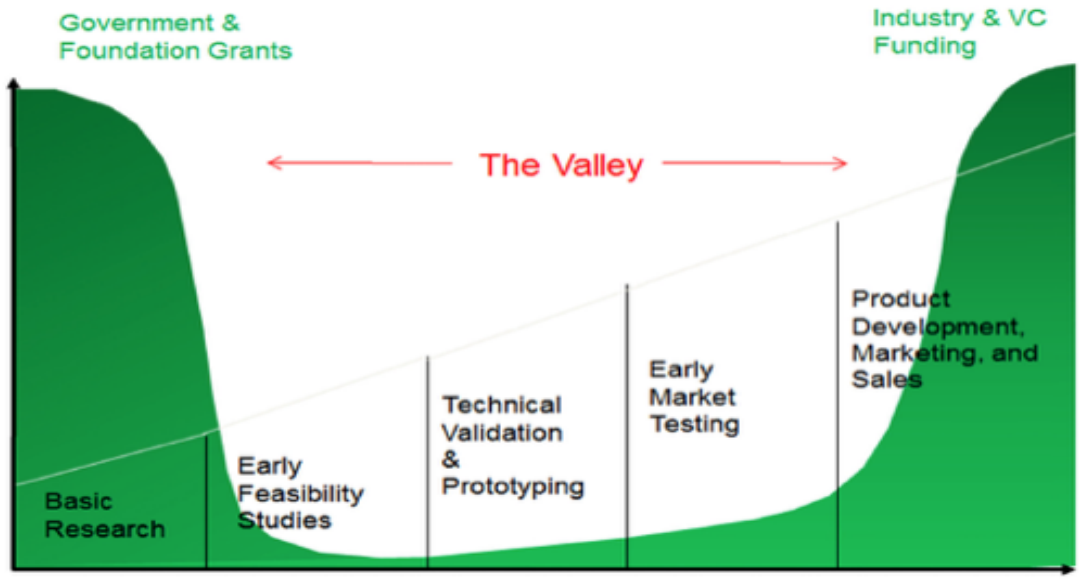

Figure 6. Schematic diagram of the so-called "valley of death" in the transition of new innovations to widely used tools.

However, embedded within the "Basic Research" segment of the figure above are two very distinct activities:

- Conceptualization of a new technology, service, or piece of software and the realization in the form of an experiment or demonstration that constitutes a successful "proof of concept."
- Conversion of a new technology from "proof of concept" into a tool used within research and development communities.

Thus, as pointed out in testimony given before Parliament in the United Kingdom,[46] it is more appropriate to think of technology development as involving two valleys of death, as shown below in Figure 7.

[46] Royal Aeronautical Society. (2012). *Written evidence submitted by Royal Aeronautical Society.* https://publications.parliament.uk/pa/cm201213/cmselect/cmsctech/348/348we03.htm

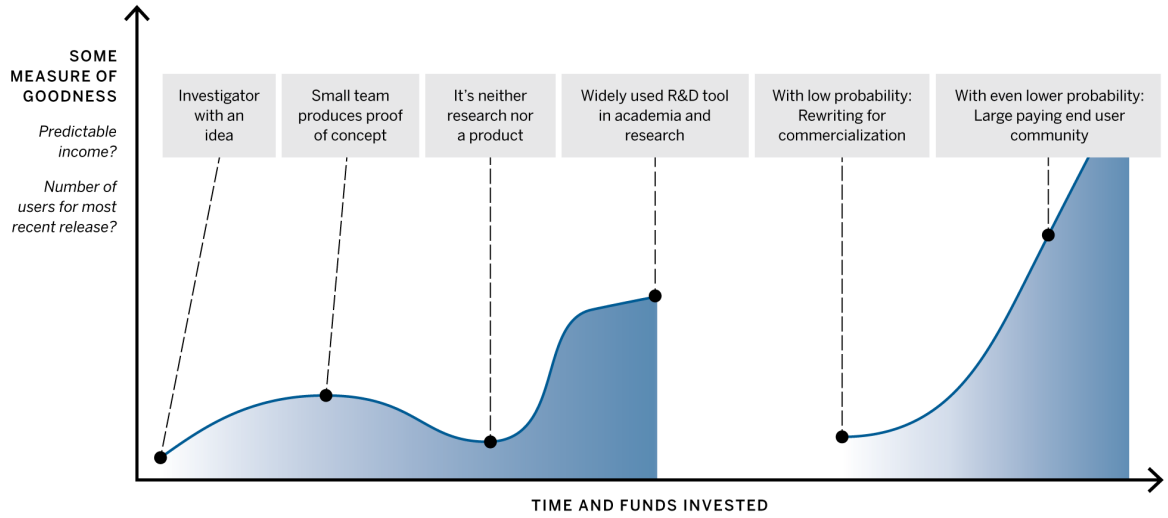

Figure 7. Two valleys of death in the life of new technology innovation and maturation, based on a figure in Royal Aeronautical Society.

Three of IU PTI's major functions relate to technology innovation and maturation and involve the evolution of technology along these valleys of death, as shown below. First, IU PTI creates new technologies and services. IU PTI spends much of its effort identifying new ideas—from Indiana University and elsewhere—and ushering them through the first valley of death to convert them into mature and widely-used tools and services within the academic research and development community. When appropriate, IU PTI also becomes directly involved in commercializing new technologies developed at Indiana University, as depicted in Figure 8.

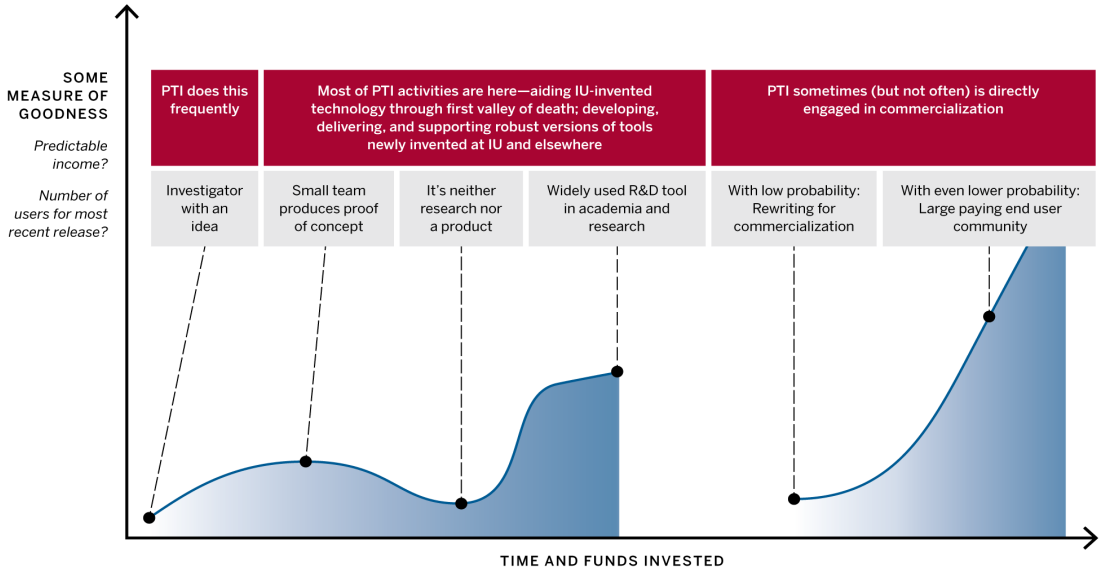

Figure 8. PTI's roles in traversing the two valleys of death.

13. Appendix 4: Details of IU PTI accomplishments

13.1. Best Papers and Posters

Year	Authors	Scope	Conference	Title
Best Paper				
2019	Wickramasinghe**, P., S. Kamburugamuve**, K. Govindarajan**, V. Abeykoon**, C. Widanage**, N. Perera**, A. Uyar**, G. Gunduz**, S. Akkas**, G.C. Fox*	International	International IEEE Conference on High Performance Big Data and Intelligent Systems	Twister2:TSet High-Performance Iterative Dataflow
2019	Rynge, M., K. Vahi, E. Deelman, A. Mandal, I. Baldin, O. Bhide**, R. Heiland*, V. Welch*, R. Hill, W.L. Poehlman, F.A. Feltus	International	PEARC19	Phil Andrews Award for Most Transformative Contribution: Integrity Protection for Scientific Workflow Data: Motivation and Initial Experiences
2018	Ruan*, G., Wernert*, E., Gnaidy*, T., Tuna*, E., & Sherman*, W.	International	PEARC18	Phil Andrews Award for Most Transformative Contribution: High Performance Photogrammetry for Academic Research.
2018	Sarajlic**, S., Chastang**, J., Marru**, S., Fischer, J., Lowe, M. (2018)	International	PEARC18	Scaling JupyterHub Using Kubernetes on Jetstream Cloud: Platform as a Service for Research and Educational Initiatives in the Atmospheric Sciences
2017	Barth, B., Gaffney, N., Gaither, K., Hempel, C., Mehringer, S., Minyard, T., Panda, D.K., Stanzione, D., Teller, P., Tufo, H., & Wernert*, E.	International	PEARC17	Phil Andrews Best Technology Paper: Stampede 2: The Evolution of an XSEDE Supercomputer. Paper presented at PEARC17, New Orleans, LA.
2016	Stewart*, C.A., Hancock*, D.Y., Vaughn, M., Fischer, J., Cockerill, T., Liming, L., Merchant, N., Miller*, T., Lowe*, J.M., Stanzione, D.C., Taylor, J., Skidmore, E.	International	PEARC16	Phil Andrews Best Technical Paper Award: Jetstream – performance, early experiences, and early results.
2015	Stewart*, C.A., Roskies, R., Knepper*, R., Moore, R.L., Whitt, J., & Cockerill, T.M.	International	PEARC15	Phil Andrews Best Technical Paper Award: XSEDE Value Added, Cost Avoidance, and Return on Investment.
2012	Devarshi Ghosha Indiana University Data to Insight Center Research Assistant and Lavanya Ramakrishnan, Lawrence Berkeley National Laboratory, USA	International	DataCloud 2012 Workshop during The International Conference for High Performance Computing, Networking, Storage and Analysis (Supercomputing/SC12) in Salt Lake City, UT, USA.	https://pti.iu.edu/centers/d2i/news/d2is-devarshi-ghoshal-wins-best-paper-award-datacloud-2012
2012	Abhishek Kulkarni**, Andrew Lumsdaine*, Michael Lang, and Latchesar Ionkov. “	International	2012 International Workshop on Runtime and Operating Systems for Supercomputers held in Venice, Italy	Best Paper – won by a student senior author! Optimizing latency and throughput for spawning processes on massively multicore processors”

2012	Thomas Sterling	International	2012 International Supercomputing Conference in Hamburg, Germany	Best Speaker award
2010	Hoefler**,T., T. Schneider, & A. Lumsdaine*.	International	SC10	Best Technical Paper, SC10: Characterizing the Influence of System Noise on Large-Scale Applications by Simulation
	Total best papers:	**11**		
Best Student Paper				
2018	Ruan, Y. ** and G.C. Fox*	International	IEEE eScience	A Robust and Scalable Solution for Interpolative Multidimensional Scaling with Weighting
	Total Best Student Papers	**1**		
Best Paper Finalists				
2018	Stewart, C.A., D.Y. Hancock, J. Wernert, M.R. Link, N. Wilkins-Diehr, T. Miller, K. Gaither, W. Snapp-Childs	International	IEEE Utility and Cloud Computing	Return on Investment for three cyberinfrastructure facilities: a local campus supercomputer; the NSF-funded Jetstream cloud system; and XSEDE (the eXtreme Science and Engineering Discovery Environment)
2015	Zeng, J. and B. Plale	International	IEEE Cluster	Workload-aware Resource Reservation for Multi-Tenant NoSQL
2014	Zeng, J., G. Ruan, A. Crowell, A. Prakash, B. Plale	International	5th Workshop on Scientific Cloud Computing, co-located with ACM High Performance Distributed Computing (HPDC)	Cloud Computing Data Capsules for Non-consumptive Use of Texts
	Total Best Paper Finalists	**3**		
Best Posters	S. Sarajlic, J. Chastang, S. Marru, J. Fischer, M. Lowe	International	PEARC 18	Scaling JupyterHub Using Kubernetes on Jetstream Cloud: Platform as a Service for Research and Educational Initiatives
	1			

Student authors are indicated above with **, authors with an affiliation with IU PTI are indicated with*.

13.2. IEEE/ACM Supercomputing Challenge Awards and Undergraduate Cluster Challenge Awards

The Supercomputing Conference is sufficiently well known that it is often referred to in print as just SCxy. The full name is the IEEE/ACM "International Conference for High Performance Computing, Networking, Storage, and Analysis" (supercomputing.org). For many years, the SCxy Conference held an advanced computing challenge. These "challenge" competitions were a way to push the envelope in capabilities of supercomputing, distributed computing, and high-speed networks. The themes varied over the years, focusing always on areas of opportunity and advancement for the international computer and computational science communities. The competition for these awards was fierce and wins were greatly coveted. One year, in fact, one of the four original supercomputer centers was IU PTI's main competition for winning the challenge and any informed observer knew that. This other center was so confident that they prepared a press release that was leaked the night before the award was announced. Luckily for IU, IU won – convincingly. In the spirit of good hearted competition, the look of dejection on the faces of the competing center was viewed as just desserts and the people involved remain friends to this day.

IU PTI and its antecedents at IU have won a total of four of these competitions over the years. None recently, as this aspect of the SCxy conference was phased out around 2010. IU PTI is by no means the leader in total wins; the original four NSF supercomputing centers have the largest number of these wins, but we believe that IU PTI has won more of these awards than any advanced computing center than the original four US supercomputing centers.

In addition to these challenges, the SCxy conference also runs a competition among student teams to run a set of software applications as quickly as possible, correctly, with a cluster in size limited by number off processors or amount of electricity that may be used.

IEEE/ACM Conference "Challenge competition" wins and honorable mentions for IU PTI and its predecessors, and Student Cluster Challenge wins

Year	Topic	Reference
Challenge award wins		
1995	The I-Way – the first national 10 Gigabit per second research network. In 1995 a group of vendors and universities came together to set up the first ever cross-country 10 Gbps network. This was a fantastically fast network at that time, and vendors only managed to keep it up for a week. During that week a number of projects demonstrated the capabilities of grid computing; this project was the proof of concept of the Grid. Mike Norman, Dennis Gannon, IU Computer Science Professor (and the first PTL Science Director), Gannon's students Pete Beckman and Kate Keahey and others were awarded an HPC Challenge award for a simulation of two galaxies colliding - a grand challenge problem in astronomy. Gannon and Beckman in particular were responsible for the distributed computing and communications that made this simulation possible.	Korab, H. M. Brown. 1995. Virtual Environments and Distributed Computing at SC'95: GII Testbed and HPC Challenge Applications on the I-WAY. http://hdl.handle.net/2022/22591 Norman, M., P. Beckman, G. Bryan, J. Dubinski, D. Gannon, L. Hernquist, K. Keahey, J. P. Ostriker, J. Shalf, J. Welling, S. Yang. 1996. Galaxies Collide On the I-Way: an Example of Heterogeneous Wide-Area Collaborative Supercomputing. The International Journal of High Performance Computing Applications. https://doi.org/10.1177/109434209601000202
1997	Distributed simulation of 3D mold filling. IU Computer Science Professor Randy Bramley led a team that ran simulations of metal casting – hot liquid metal filling castings to pour wheel rims – that spanned two continents and three supercomputers. This was given first place in the HPC challenge that year for having the highest effective rate of computations of any application demonstrated as part of the HPC Challenge competition.	
2003	Global analysis of arthropod evolution. Associate Dean Craig Stewart led an international team that assembled a grid of hundreds of processors in dozens of supercomputers spanning every continent on earth save Antarctica to analyze the evolutionary relationships of insects. This was, as far as we know, the largest grid of supercomputers ever assembled to that date, and the results confirmed emerging new ideas about the	Stewart, C.A. R. Keller, R. Repasky, M. Hess, D. Hart, M. Mueller, R. Sheppard, U. Woessner, M. Aumueller, Huian Li, D.K. Berry, J. Colbourne. 2004. A global grid for analysis of arthropod evolution. pp. 328-337 In R. Buyya (ed.)

	insects (and in particular that they are not a single evolutionary unit). This team was led by IU and by HLRS, the high performance computing center of the University of Stuttgart, but included many universities and most of the major supercomputer centers in the US. This project won a special competition at SC03 for "most distributed computation."	Proceedings: Fifth IEEE/ACM International Workshop on grid computing. 8 November 2004, Pittsburgh, PA. http://portal.acm.org/citation.cfm?id=1033261
2007	In 2006 and 2007 there was a special competition called the "Bandwidth Challenge. " IU lead a team with the ZIH (High Performance Computing Center) of Technische Universitaet Dresden and other institutions as partners entitled "Serving as a model." Led by IU's Stephen Simms, this project depended on the high I./O capabilities of the IU Data Capacitor, a system designed to store and manipulate massive data sets. The IU=led team achieved a peak transfer rate of 18.21 Gigabits/second out of a possible maximum of 20 Gigabits/second. This performance was nearly twice the peak rate of the nearest competitor. "This project simultaneously pushed the limits of networking and storage technology while demonstrating a reproducible model for remote data management. Best of all, we did this using a variety of research applications that we support every day at Indiana University," said Data Capacitor and Bandwidth Challenge project leader Stephen Simms.	https://newsinfo.iu.edu/news/page/normal/6839.html Kluge, M., S. Simms, T. William, R. Henschel, A. Georgi, C. Meyer, M.S. Mueller, C.A. Stewart, W. Wünsch, & W.E. Nagel. "Performance and quality of service of data and video movement over a 100 Gbps testbed." Future Generation Computer Systems, 29(1), 230-240. 2013. http://dx.doi.org/10.1016/j.future.2012.05.028
Challenge award Honorable Mentions		
2006	2006 was Stephen Simm's first attempt at the Bandwidth challenge competition. With participation, notably, of Data to Insight Center Director Beth Plale, Simms led a team in a project that focused on supporting a number of important high performance computing software applications over long haul high speed networks. Entitled "All in a day's work," this project was designated as Honorable Mention (runner up) at the SC06 Bandwidth Challenge.	https://www.researchgate.net/publication/220782989_Bandwidth_challenge---All_in_a_day%27s_work_advancing_data-intensive_research_with_the_data_capacitor
Student Cluster Competition Wins		
2008	In 2008 the "Counterfeiters" won the SC cluster challenge. This team was made up of students from the Open Systems Lab and students from the Technische Universitaet Dresden – one of many achievements in this long running collaboration.	https://newsinfo.iu.edu/news/page/normal/9354.html

13.3. Conferences led or hosted by IU PTI

Year	Conference	Location	Led or Hosted	Who	Role	Conference or Final Report URL	# of events
2020	PEARC20 - Practical Experiences in Advanced Research Computing	Virtual	Led	Craig Stewart Julie Wernert	Technical Chair Evaluation Chair	https://pearc.acm.org/pearc20/	1
2010-2019, annually	CACR Cybersecurity Conference	Bloomington or Indianapolis, IN	Led	Von Welch	General Chair	https://cacr.iu.edu/events/cybersecurity-summit.html	10
2019	CAAV 19 (Campus Alliance for Advanced Visualization)	Bloomington, IN	Hosted	Bill Sherman, Robert Ping	Local Arrangements chairs	https://rt.iu.edu/thecaav19/index.html	1
2019	HUF (HPSS User Forum)	Bloomington, IN	Hosted	Charles McClary	Local Arrangements Chair	https://itnews.iu.edu/articles/2019/HUF19-call-for-presentations.php	1
2019	IEEE Cloud	Milan, Italy	Led	Geoffrey Fox	General Chair	https://conferences.computer.org/cloud/2019/	1
2019	IEEE International Congress on Big Data	Milan, Italy	Led	Beth Plale	Program Chair	https://conferences.computer.org/bigdatacongress/2019/	1
2019	PEARC19	Chicago, IL	Led	Julie Wernert	Evaluations Chair	https://www.pearc19.pearc.org	1
2018	IEEE Cloud	San Francisco	Led	Geoffrey Fox	General Chair	https://conferences.computer.org/cloud/2018/	1
2018	PEARC18	Pittsburgh, PA	Led	Julie Wernert	Evaluations Chair	https://www.pearc18.pearc.org	1
2018	CUG 2018	Stockholm, Sweden	Led	David Y. Hancock	General Chair	https://cug.org/cug-2018/	1
2017	LUG 2017	Bloomington, IN	Led	Stephen Simms	General Chair	http://opensfs.org/lug-2017/	1
2017	PEARC17	New Orleans, LA	Led	Julie Wernert	Logistics Co-Chair	https://www.pearc17.pearc.org	1
2017	CUG 2017	Redmond, WA	Led	David Y. Hancock	General Chair	https://cug.org/cug-2017/	1
2016	GCC 2016 - Galaxy Community Conference	Bloomington, IN	Hosted	Robert Ping, Craig Stewart	Local Organizing Chair	https://gcc16.sched.com/	1
2016	LUG 2016	Portland, OR	Led	Stephen Simms	Program Chair	http://opensfs.org/events/lug-2016/	1
2016	XSEDE 16Conference	Miami, FL	Led	Julie Wernert	Logistics Co-Chair	https://dl.acm.org/doi/proceedings/10.1145/2949550	1
2016	CUG 2016	Chicago, IL	Led	David Y. Hancock	General Chair	https://cug.org/cug-2016/	1
2015	LUG 2015	Denver, CO	Led	Stephen Simms	Program Chair	http://opensfs.org/events/lug-2015/	1
2015	CUG 2015	London, England	Led	David Y. Hancock	General Chair	https://cug.org/cug-2015/	1
2015	SPXXL	Maui, HI	Led	David Y. Hancock	VP		1
2014	PRAGMA27	Bloomington, IN	Led	Beth Plale	General Chair	http://www.pragma-grid.net/meetings/	1

						pragma-27-presentations/	
2014	CUG 2014	Lugano, Switzerland	Led	David Y. Hancock	General Chair	https://cug.org/cug-2014/	1
2014	HPDC 2014 - ACM High Performance Distributed Computing	Vancouver, BC	Led	Beth Plale	General Chair	http://www.hpdc.org/2014/	1
2014	SPXXL	Fort Lauderdale, FL	Led	David Y. Hancock	VP		1
2014	SPXXL	Chicago, IL	Led	David Y. Hancock	VP		1
2013	CUG (Cray User Group)	Napa Valley, CA	Led	David Y. Hancock	VP & Program Chair	https://cug.org/cug-2013/	1
2013	IEEE Cluster 13	Indianapolis, IN	Led	Craig Stewart	General Chair	https://ieeecluster13conference.sched.com/	1
2013	ICWS 2013 - 2013 IEEE 20th International Conference on Web Services	Santa Clara, CA	Led	Beth Plale	Program Chair	https://doi.org/10.1109/ICWS30647.2013	1
2013	HTRC Un-Camp	Bloomington, IN	Led	Beth Plale	General Chair	https://www.hathitrust.org/htrc_uncamp2013	1
2013	SPXXL	Maui, HI	Led	David Y. Hancock	VP		1
2013	SPXXL	Lugano, Switzerland	Led	David Y. Hancock	VP		1
2012	CUG (Cray User Group)	Stuttgart, Germany	Led	David Y. Hancock	VP & Program Chair	https://cug.org/1-conferences/CUG2012/	1
2012	HTRC Un-Camp	Bloomington, IN	Led	Beth Plale	General Chair	https://www.hathitrust.org/htrc_uncamp2012	1
2012	XSEDE12	Chicago, IL	Led	Craig Stewart	General Chair	https://dl.acm.org/doi/proceedings/10.1145/2335755	1
2012	SPXXL	Miami, FL	Led	David Y. Hancock	VP		1
2012	SPXXL	Toronto, Canada	Led	David Y. Hancock	VP		1
2011	CUG (Cray User Group)	Fairbanks, Alaska	Led	David Y. Hancock	VP & Program Chair	https://cug.org/1-conferences/CUG2011/	1
2011	SPXXL	Maui, HI	Led	David Y. Hancock	VP		1
2011	SPXXL	Paris, France	Led	David Y. Hancock	VP		1
2010	International Conference on Cloud Computing (CloudCom 2010)	Indianapolis, IN	Led	Geoffrey Fox	General Chair	http://2010.cloudcom.org/	1
2010	SPXXL	Maui, HI	Led	David Y. Hancock	VP		1
2010	SPXXL	San Francisco, CA	Led	David Y. Hancock	VP		1
2009	SPXXL	Barcelona, Spain	Led	David Y. Hancock	VP		1
2008	TeraGrid08	Indianapolis, IN	Led	D. Scott McCaulay	General Co-Chair	http://archive.teragrid.org/events/teragrid08/index.htm	1

2008	4th IEEE International Conference on e-Science	Indianapolis, IN	Led	Geoffrey Fox	General Chair	https://escience2008.iu.edu/	1
2007	3rd IEEE International Conference on e-Science and Grid Computing	Bangalore, India	Led	Geoffrey Fox	Program Chair	http://www.escience2007.org/	1
2007	OGF21 - The 21st Open Grid Forum	Seattle, WA	Led	Geoffrey Fox	Program Chair	https://www.ogf.org/OGF21/events_program_ogf21.php	1
2006	GGF16 - The 16th Global Grid Forum	Athens, Greece	Led	Geoffrey Fox	Program Chair	https://www.ogf.org/GGF16/ggf_events_ggf16.htm	1
2006	GRID 2006 - 7th IEEE/ACM International Conference on Grid Computing	Barcelona, Spain	Led	Beth Plale	Program Vice Chair	https://dl.acm.org/doi/proceedings/10.5555/1513923	1
2005	GCC 2005, The 4th International Conference on Grid and Cooperative Computing	Beijing, China	Led	Geoffrey Fox	Program Co-Chair	https://dl.acm.org/doi/proceedings/10.5555/2112362	1
2005	GGF14 - The 14th Global Grid Forum	Chicago, IL	Led	Geoffrey Fox	Program Chair	https://www.ogf.org/ggf_events_ggf14.htm	1
2005	I-Light Conference	Indianapolis, IN	Led	Eric Wernert	Program Co-Chair	http://hdl.handle.net/2022/435	1
2004	I-Light Conference	Indianapolis, IN	Led	Craig Stewart	Program Co-Chair	http://hdl.handle.net/2022/13999	1
2002	Java Grande-ISCOPE 2002	Seattle, WA	Led	Geoffrey Fox	Program Chair	https://dl.acm.org/doi/proceedings/10.1145/583810	1
2002	I-Light Conference	Indianapolis, IN	Led	Michael McRobbie	Program Co-Chair	http://hdl.handle.net/2022/14002	1
	Total conferences						64

Table A3.3-1. Conferences led or hosted by IU PTI.

13.4. Major services offered by PTI in support of R&D

Major services created by IU PTI are listed in the table below. This listing does not include services offered by Research Technologies under funding primarily from Indiana University general funds accounts. Highlights of such locally-funded services that are primarily relevant to the IU community is online at pti.iu.edu/impact/timeline

Major service / software / project	Center / Lab	IU Project Leader	Active from - till ("YYYY-=s still active)	URL	Scope	Description
Election security for2020 elections in Indiana	CACR	Von Welch	2019 -	https://cacr.iu.edu/projects/election%20security/index.html	State	CACR is providing consulting on preparation for and reaction to cybersecurity incidents for all 92 Indiana counties in preparation for the 2020 general election
SecureMyResearch	CACR	Von Welch	2019 -	https://cacr.iu.edu/projects/SecureMyResearch/index.html	National	Secure research virtualization environment for IU
ResearchSOC	CACR	Von Welch	2018 -	https://researchsoc.iu.edu	National	NSF-funded collaborative security response center that addresses the unique cybersecurity concerns of the NSF research
PACT - Principles-Based Assessment for Cybersecurity Toolkit	CACR	Von Welch	2018 -	https://CACR.iu.edu/pact/index.html	National	Cybersecurity Assessment built around Information Security Practice Principles
OmniSOC - Security Operations Center	CACR	Von Welch	2017 -	https://omnisoc.iu.edu	National	Membership organization, goal to minimize the time from first awareness of a threat anywhere to mitigation everywhere for its members
Software Assurance Marketplace	CACR	Von Welch	2012 -		National	Tools and consulting service to ensure scientific software is safe from hacking
TrustedCI	CACR	Von Welch	2012 -	https://www.trustedci.org	National	The National Science Foundation Cybersecurity Center of Excellence
Science Gateway Security Services - Custos	CIRC	Marlon Pierce	2018 -	https://github.com/apache/airavata-custos	National	NSF Award #1840003, CICI: SSC: Securing Science Gateway Cyberinfrastructure with Custos. Custos is a spinoff of Apache Airavata security services. It provides online security services for science gateways, including identity management and group management.
Science Gateways Community Institute	CIRC	Marlon Pierce	2015 -	https://sciencegateways.org	National	Science Gateways Community Institute, NSF Award #1547611. Pierce is Co-PI on this award lead by SDSC. SGCI is an NSF software institute that provides services and community building support for the national science gateway community.
Science Gateways Platform as a Service (SciGaP)	CIRC	Marlon Pierce	2013 -	https://scigap.org	National	SciGaP is a hosted science gateway platform operated by CIRC that hosts over 35

						science gateways. Prominent examples include SEAGrid (chemistry), UltraScan (biophysics), dREG (bioinformatics), SimVascular (vascular system modeling), SearchSRA (bioinformatics), and InterACTWEL (food-energy-water nexus modeling).
Science Gateways	CIRC	Marlon Pierce	2007 -		National	CIRC provides the resources, aoftware, and support used by a total of #! science gateways as of the writing of this report
Apache Airavata	CIRC	Marlon Pierce	2004 -		National	Apache Airavata is a widely used middleware toolkit for building science gateways
Komadu	D2I	Beth Plale	2015 -	https://github.com/Data-to-Insight-Center/komadu	National	Provenance collection and visualization tool based on W3C PROV standard
SEAD - Sustainable Environments - Actionable Data	D2I	Beth Plale	2011 - 2017	http://sead-data.net	National	Data curation, management, and sharing tools; toolkit still available through National Data Services
Karma	D2I	Beth Plale	2006 - 2015		National	Provenance management
LEAD - Linked Environments for Atmospheric Discovery	D2I	Beth Plale	2003 - 2009		National	Pioneered the concept of science gateways and advanced models for automated metadata capture. Demonstration of curated collection of weather forecasts. See Vortex2 2010 collection at https://scholarworks.iu.edu/dspace/handle/2022/14983
Data capsule	D2I	Beth Plale	2011 on - active as part of HTRC		National	The data capsule concept implemented a secure "container" within which sensitive data could be analyzed, and then from which non-sensitive data could be extracted. This was pioneered for text analysis of copyrighted data that were part of the Google Books project. By "nonconsumptive research" we mean that a protected text can be analyzed, and pieces may be extracted, but it is not possible to extract an entire document so as to "consume" it as a complete written document
E-RPID - Robust Persistent ID Testbed	D2I and CIRC	Beth Plale and Robert Quick	2017 - active	https://rpidproject.github.io/rpid/	National	Testbed for Handles for science that utilize PID Kernel Information. Runs local handle server.
RaPyDLI - Rapid Python Deep Learning Infrastructure	DSC	Geoffrey C. Fox	2015 -	http://rapydli.org	National	Combine high level Python, C/C++ and Java environments with carefully designed libraries supporting GPU accelerators and MIC coprocessors for deep learning applications

FutureSystems	DSC	Geoffrey C. Fox	2015 -	https://www.dsc.soic.indiana.edu/futuresystems	National	Resources for experimentation with cloud computing software
IPCC - Intel Parallel Computing Center at Indiana University	DSC	Judy Qiu Fox	2014 - 2018	http://ipcc.soic.iu.edu/index.html	National	Implementation and performance optimization of software on Intel processors
SPIDAL	DSC	Geoffrey C. Fox	2014 -	http://www.spidal.org/index.html	National	The goal for the SPIDAL project is to create software abstractions to help connect communities together with applications in different scientific fields (Includes MIDAS architecture and activities)
Comet	DSC	Geoffrey C. Fox	2013 - 2021	https://www.sdsc.edu/services/hpc/hpc_systems.html#comet	National	DSC provided critical software used in the deployment of the NSF-funded Comet Supercomputer (project led by San Diego Supercomputer Center)
MSI-CIEC - Minority Serving Institution - CyberInfrastructure Empowerment Consortium	DSC	Geoffrey C. Fox	2010 on; semi-active	http://www.msi-ciec.us	National	Dedicated to building and enhancing the social and technological mechanisms for meaningful engagement of MSIs in cyberinfrastructure
FutureGrid	DSC	Geoffrey C. Fox	2010 - 2015	http://archive.futuregrid.org	National	Nationally-accessible distributed system for grid and cloud computing experiments
Twister	DSC	Judy Qiu Fox	2010 -	http://www.iterativemapreduce.org	National	Iterative MapReduce
Cloudmesh	DSC	Geoffrey C. Fox	2010 - 2014	http://cloudmesh.github.io	National	Manage virtual machines and bare metal provisioned operating systems in a multicloud environment
OGCE - Open Grid Computing Environments	DSC	Marlon Pierce, Geoffrey C. Fox	2010 - 2013	https://www.nsf.gov/awardsearch/showAward?AWD_ID=1032742	National	reusable components and services for constructing Grids
Chemical Informatics and Cyberinfrastructure Collaboratory	DSC	Geoffrey C. Fox	2005 - 2007	http://dsc.soic.indiana.edu/presentations/CICCOct21-05/CICC%20research%20plan%209_30_2005.pdf	National	NIH-funded system for managing and discovering cheminformatics information
SALSA - Service Aggregated Linked Sequential Activities	DSC	Judy Qiu Fox	2003 - 2017	http://salsahpc.indiana.edu	National	Scalable and composable software system
Narada Brokering	DSC	Geoffrey C. Fox	2001 - 2009	https://dl.acm.org/doi/10.5555/646439.693397	National	Event broker and distribution system that supported Grid and web services
GlobalMMCS (MultiMedia Collaboration System)	DSC	Geoffrey C. Fox	2001-2004	http://grids.ucs.indiana.edu/ptliupages/publications/SC04_pstr_GlobalMMCS.pdf	National	integration of several different audio/video technologies through the use of service oriented architectures, software messaging
Tango	DSC	Geoffrey C. Fox	2001 (at IU)	https://surface.syr.edu/cgi/viewcontent.cgi?article=1076&context=npac	National	Collaborative environment for World Wide Web
High Performance Java	DSC	Geoffrey C. Fox	2001 (at IU)	http://www.hpjava.org	National	hi Performance Computing implementation of Java programming language
HathiTrust Research Center Analytics	HTRC	John Walsh	2015 -		National	Supports large-scale computational analysis of the works in the HathiTrust Digital

						Library to facilitate non-profit and educational research.
Research Software Portal	NCGAS	Tom Doak	2018 -	https://software.xsede.org	National	Source of easily downloadable bioinformatics software
Bioinformatics software maintained on XSEDE-allocated supercomputer and cloud systems	NCGAS	Tom Doak	2011 -		National	NCGAS makes software and computer resources available to allocated user groups o IU systems (currently Carbonate) as well as NSF-funded systems including Jetstream and Bridges
HARC - Humans Advancing Research in the Cloud	Office of Exec. Dir.	Brian Voss / Craig Stewart	2018 -	harc.iu.edu	National	Education / collaborative project to identify needs for support of research computing done in clouds
Cyberinfrastructure Assessment and Evaluation	Office of Exec. Dir.	Julie Wernert	2018 -	https://pti.iu.edu/centers/executive-director/index.html	National	Contract assessment services for cyberinfrastructure systems, services, and conferences
ROI (Return on Investment) analysis	Office of Exec. Dir.	Craig Stewart	2014 -	https://pti.iu.edu/centers/executive-director/index.html	National	ROI analysis regarding investments in cyberinfrastructure; IU staff have published more peer-reviewed papers about ROI for advanced cyberinfrastructure than anyone else in the US
Science Node	Office of Exec. Dir.	Craig Stewart	2012 -	sciencenode.org	National	PTI is responsible for raising underwriting funds to support operation of Science Node, which is now ready by more than 140,000 people internationally
Green 500 list		Andrew Lumsdaine		http://www.green500.org		Ranking of systems among the top 500 fastest in the world ranked by how energy-efficient they are
HPX+	CREST / Open systems Lab	Thomas Sterling	2011 - 2018	https://en.wikipedia.org/wiki/HPX	National	Low latency runtime system
LAMMPI	CREST / Open systems Lab	Andrew Lumsdaine	2002 - 2016	https://en.wikipedia.org/wiki/LAM/MPI	National	Widely used MPI implementation
OpenXDMOD-VA - Open SD Metrics on Demand Value Analytics	RT	Matthew Link / Craig Stewart	2016 -	https://open.xdmod.org/8.5/index.html	National	Value Analytics module for OpenXDMOD - allowing users to relate grant award receipts to use of advanced CI facilities provided by an organization
Big Red II + Supercomputer	RT	Craig Stewart / Matt Link	2015-2019	https://kb.iu.edu/d/bcqt	National	Experimental system for large scale parallelism
Jetstream	RT	David Y. Hancock / Craig Stewart	2014 -	jestream-cloud.org	National	First NSF-funded cloud system for nationwide, production use supporting all areas of research
Big Red II Supercomputer	RT	Craig Stewart / Matt Link	2013 - 2019	https://kb.iu.edu/d/alde	National	First 1 PetaFLOPS supercomputer owned by a US university for use by its own university community
Science on a Sphere	RT	Eric Wernert	2014 -	https://itnews.iu.edu/articles/2013/ius-science-on-a-sphere-offers-new-way-to-visualize-data-on-a-global-scale-.php	State	“Spherical Screen” visualization system for visualizing data about anything spherical or approximately so - from data on our planet to the history of World Cup soccer balls.

Wrangler	RT	Steve Simms/ Craig Stewart	2013 -	https://www.tacc.utexas.edu/systems/wrangler	National	RT operated half of the disk storage space for the TACCC-led Wrangler project
Stampede & Stampede 2	RT	Eric Wernert / Esen Tuna / Craig Stewart	2011 - 2021	https://www.tacc.utexas.edu/systems/stampede	National	RT provided consulting expertise on the implementation and benchmarking of R and other machine learning and graph processing libraries, especially on the Intel Xeon Phi architecture
IQ-Table	RT	Eric Wernert	2012 -	https://scholarworks.iu.edu/dspace/bitstream/handle/2022/21866/iq_tables_and_touch_enabled_workflows_Fall17.pdf?sequence=1&isAllowed=y	State	Touch - interactive visualization system
IQ-Tilt stereoscopic display systems	RT	Eric Wernert	2012 -	http://avlfeed.blogspot.com/2012/12/indiana-university-advanced.html	State	Wernert and his staff designed and published plans for creating a series of stereoscopic display devices (IQ-Table, IQ-Tilt, IQ-Wall, IQ-Station, IQ-Force)
IQ-Wall	RT	Eric Wernert	2012 -	https://kb.iu.edu/d/avzq	National	High resolution, low cost visualization system. As of 2020, 19 have been deployed at IU and 5 at other institutions.
Operation Ice Bridge	RT	Matthew Link / Rich Knepper	2009 -	https://www.nasa.gov/mission_pages/icebridge/index.html	National	RT staff travel annually to Antarctica and are responsible for data management for Operation Icebridge, which measures thickness and status of Antarctic ice sheets
Open Science Grid	RT	Rob Quick / Craig Stewart	2009 - 2017	https://opensciencegrid.org	National	RT operated the Grid Operations Center for OSG, responsible for 7 x 24 operational support of OSG and development of software supporting OSG operations
Big Red supercomputer	RT	Craig Stewart / Matt Link	2009 - 2013	https://newsinfo.iu.edu/news/page/normal/3660.htmlIf	State	23rd fastest unclassified supercomputer in the world on Top500 list. Made available to business operating through the State of Indiana as part of the activities of the Indiana Economic Development Commission
PolarGrid	DSC, RT	Geoffrey C. Fox / David Y. Hancock	2007 - 2009		National	NSF funded cluster (MRI grant) - Cluster used by US Antarctic research community to analyze Antarctic ice thickness and characteristics
REDCap	RT	Richard Meraz	2008 -	https://indianactsi.org/researchers/services-tools/translational-informatics/redcap/	National	REDCap is a self-managed, secure, web-based platform that is designed to support data collection and data management for research, operations support and quality improvement projects including management of protected health information in a way that is aligned with HIPAA.

Mason	RT	Craig Stewart/ David Hancock	2010-2015		National	IU provided a part of the Mason large memory system to the NSF funded XSEDE Community.
National Gene Vector Biorespository	RT	Therese Miller / Robert Henschel	2016-	https://www.ngvbcc.org	National	RT, in collaboration with the Indiana University School of Medicine's Bioinformatics Core, have built and are maintaining and extending the web-based information systems used to manage and share information.
One Degree Imager Pipeline Portal and Archive	RT	Robert Henschel / Arvind Gopu	2010 -	https://odi.iu.edu/	National	The ODI Pipeline, Portal, and Archive is a web science gateway that provides astronomers a single point of access to ODI data, and rich computational and visualization capabilities.
TeraGrid Resource Partner - shared disk storage	RT	Stephen Simms	2005 - 2009	https://en.wikipedia.org/wiki/TeraGrid	National	IU provided PetaByte + disk storage for use by the national research community through the TeraGrid, provided by the IU Data Capacitor
Ready, Set, Robots! Camp	RT	Robert Ping	2003 -	https://www.youtube.com/watch?v=zWh9hWf0rBM	Bloomington region	Summer camp for middle- and high - school students
TeraGrid Resource Partner - computation	RT	Craig Stewart	2003 - 2007	https://en.wikipedia.org/wiki/TeraGrid	National	IU provided 1 TFLOPS IBM SP and 1.3 TFLOPS Distribut5ed Linux Cluster (AVIDDS) for use by the national research community via TeraGrid, with NSF funding
AVIDD – Analysis and Visualization of Instrument-Driven Data (cluster)	RT	Craig Stewart / George Turner	2001-2005	https://www.nsf.gov/awardsearch/showAward?AWD_ID=0116050&HistoricalAwards=false	National	First distributed Linux Cluster to achieve more than 1 TeraFLOPS on Linpack Benchmark; one of the first services of IU offered to the national research community through the TeraGrid
Research SP supercomputer	RT	Craig Stewart / Mary Papakhian	2001 - 2005	https://www.hpcwire.com/2001/10/19/indiana-u-ibm-unveil-largest-university-owned-supercomputer/	National	First 1 TeraFLOPS supercomputer owned by a US university for use by its own university community; ; one of the first services of IU offered to the national research community through the TeraGrid
Virtual Reality Theatre	RT	Eric Wernert	2000-2012	https://kb.iu.edu/d/bcpb	State	High resolution stereoscopic room size display - CAVE or 30' wall
fastDNAml - Fast DNA maximum likelihood	RT	Craig Stewart	2000 - 2004	https://sourceforge.net/projects/iupfastdnaml/	National	Widely used phylogenetic inference software; core of fastDNAml was used to create RAXml, its successor in terms of use within the bioinformatics community.
John - e - Box	RT	Eric Wernert, John N. Huffman, John C. Huffman	1909-2004	https://dl.acm.org/doi/abs/10.1145/1095242.1095269	National	1 meter cube stereoscopic visualization system, perfect for labs, museum displays, etc.
CAVE (CAVE Automatic Visualization Environment)	RT	Eric Wernert, John Huffman	1997-2005	https://en.wikipedia.org/wiki/Cave_automatic_virtual_environment	State	IU had one of the first CAVE VR environments at any university in the US. It was a major attraction offering a 10'

						immersive VR environment. Among the many distinguished visitors to tour IU's CAVE was Mikhail Gorbachev, who was quite pleased that AVL programmers had added a model of the Mir space station into a 3D visualization of our solar system
Immersadesk	RT	Eric Wernert, John Huffman	1997 2003	https://www.evl.uic.edu/entry.php?id=1770	State	A "drafting-table scale" stereoscopic display. The first stereoscopic display installed at the IUPUI Campus
Total	72					

Table 4.1. Major services created by IU PTI.

13.5. Open source software created by IU PTI

The table below is ordered by the center creating a particular product. Within centers, individual titles are listed in order of most recent year active. Note that this is a list of distinct titles rather than releases. Some earlier rereports counted the total number of releases, which is a much higher number.

Software Title	Year Created	Last year actively maintained	Description	Project leader	Center	url	Other reference
SWAMP-in-a-box	2016	2020	Software Assurance Marketplace (SWAMP) software for download and local execution	Welch	CACR/ ANML	https://github.com/mirswamp/deployment	
Roo	2004	2006	"Honeypot" network security software	Wallace	CACR/ ANML	https://www.honeynet.org/projects/old/honeywall-cdrom/	https://itnews.iu.edu/articles/2005/advanced-network-management-lab-and-honeynet-project-release-third-generation-security-software.php
SpoofWatch	2002	2003	Detects IP packets using spoofed source addresses, to identify Distributed Denial of Service (DDoS) attack.	Wallace	CACR/ ANML	https://www.snort.org/	
Tsunami	2002	Active	A fast user-space file transfer protocol for transfer over very high speed long distance networks, started by ANML at IU. Aalto University Metsähovi Radio Observatory took over management of the code in 2009.	Wallace	CACR/ ANML	https://newsinfo.iu.edu/web/page/normal/588.html	
GeoGateway	2016	Active	A data product search and analysis gateway for scientific discovery, field use, and disaster response	Pierce	CIRC	https://github.com/GeoGateway/	
Apache Airavata	2004	Active	Apache project - Tools for building scientific workflows and science gateways involving distributed computers, data sources, and users.	Pierce	CIRC	http://airavata.apache.org	
Apache Airavata PGA	2015	Active	Apache Airavata PHP reference implementation	Pierce	CIRC	https://github.com/apache/airavata-php-gateway	

Custos	2018	Active	New cybersecurity software for science gateways	Pierce	CIRC	https://airavata.apache.org/custos/	
Apache Rave	2015	2016	Open Social and W3C Widget-compliant Web portal software for building Science Gateways.	Pierce	CIRC	http://rave.apache.org	
SciGaP	2013	Active	Science Gateway Platform as a Service (SciGaP) provides application programmer interfaces (APIs) to hosted infrastructure to create Science Gateways.	Pierce	CIRC	https://github.com/SciGaP/	https://scigap.org/ https://www.nsf.gov/awardsearch/showAward?AWD_ID=1339774
HPX+	2011	2018	High Performance ParallaX runtime system	Sterling	CREST		
MPI.NET	2013	2015	High-performance parallel computing in C#		CREST/OSL	https://github.com/mpidotnet/MPI.NET	
Boost graph library	2003	2015	Software Library for graph analysis	Lumsdaine	CREST/OSL	https://www.boost.org/	
LAM-MPI	2003	2015	Predecessor to OpenMPI	Lumsdaine	CREST/OSL	https://blogs.cisco.com/performance/a-farewell-to-lammpi	
Contributions to Open MPI	2012	2015	Parallel computing software library led by other instructions; IU contributed components	Lumsdaine	CREST/OSL	https://www.open-mpi.org	
ConceptGCC	2006	2010	“generic programming” support GNU C++ compiler	Lumsdaine	CREST/OSL	https://gcc.gnu.org/onlinedocs/gcc/C_002b_002b-Concepts.html	
Avalon Media System	2013	Active	Open source system for providing online access to audio and video collections	Plale	D2I	https://github.com/avalonmediasystem/avalon	
Flange	2018	Active	Language for IoT and Fog computing devices	Swany	D2I	https://ieeexplore.ieee.org/document/8822006	
HTRC Secure Commons	2015	Active	Suite of services provisioning computational analysis to the nearly 17 million digitized books (70% in copyright) in the HathiTrust digital library.	Plale / Walsh	HTRC/D2I	https://github.com/htrc	
HTRC Data Capsules	2011	Active	Secure environment for text analysis at scale of sensitive digitized content.	Plale	HTRC/D2I	https://github.com/htrc/HTRC-DataCapsules	

Phoebus	2016	Active	Data movement service	Swany	D2I	http://damsl.cs.indiana.edu/projects/phoebus	
Curbee	2016	2018	Suite of microservices applied to research objects to enhance (curate) them for publication.	Plale	D2I	https://github.com/Data-to-Insight-Center/sead2/tree/master/sead-api https://github.com/Data-to-Insight-Center/Curbee	
Komadu	2015	2018	Provenance collection tool that can be added to an existing cyberinfrastructure for the purpose of collecting and visualizing data provenance. Komadu is a redesign of Karma	Plale	D2I	https://github.com/Data-to-Insight-Center/komadu https://pti.iu.edu/impact/data-sets/komadu.html	*Suriarachchi, I., Zhou, Q., & Plale, B. (2015). Komadu: A Capture and Visualization System for Scientific Data Provenance. Journal of Open Research Software, 3(1), e4. DOI: http://doi.org/10.5334/jors.bq*
SEAD Matchmaker	2016	2018	Recommendation engine that acts as matchmaker between people, data, and repositories to identify the most appropriate repositories for publication and publishing of research data objects.	Plale	D2I	https://github.com/Data-to-Insight-Center/sead2/tree/master/sead-matchmaker https://github.com/Data-to-Insight-Center/Data-MatchMaker	
SEAD - Sustainable Environments - Actionable Data	2011	2017	Data curation, management, and sharing tools; toolkit still available through National Data Services	Plale	D2I	http://sead-data.net	
SEAD-IU Cloud	2016	2017	Storage and publication option for SEAD users.	Plale	D2I	https://github.com/Data-to-Insight-Center/sead2/tree/master/sda-agent https://github.com/Data-to-Insight-Center/IU-SEAD-Cloud	
Kuali OLE 1.6	2010	2016	Open Library Environment	Plale	D2I	https://openlibraryenvironment.org/ http://www.kuali.org/download (broken link)	https://kb.iu.edu/d/aztj https://www.zambianlibrarian.com/post/sad-news-kuali-ole-is-defunct https://journals.ala.org/index.php/ltr/article/view/6407/8456

Karma	2006	2015	The Karma tool is a standalone tool that can be added to existing cyberinfrastructure for recording of provenance data. purposes of collection and representation of provenance data.	Plale	D2I	http://d2i.indiana.edu/provenance_karma https://pti.iu.edu/impact/open-source/karma.html https://sourceforge.net/projects/karmatool/ (broken link)	
PhotoCat2	2011	2015	Image cataloging tool	Plale	D2I	https://github.com/iudlp/photocat2	https://github.com/IUBLibTech/photocat2
XSP	2012	2015	Network library	Swany	D2I	http://damsl.cs.indiana.edu/projects/phoebus/xsp.php	
NetKarma	2009	2013	NetKarma allows researchers to see the exact state of the network and store configuration when running network experiments.	Plale	D2I	http://d2i.indiana.edu/provenance_netkarma (broken link) https://pti.iu.edu/impact/open-source/karma.html https://sourceforge.net/projects/karmatool/	
NetKarma plugin to Cytoscape	2009	2013	Connector from NetKarma to Cytoscape software	Plale	D2I	http://d2i.indiana.edu/provenance_netkarma (broken link) https://pti.iu.edu/impact/open-source/netkarma.html	
RIS2N3	2011	2012	Converts RIS citation format to N3 format for loading into VIVO.	Plale	D2I	https://github.com/dgcliff/RIS2N3	
XMC Cat	2008	2012	Metadata catalog that stores metadata describing data objects that are themselves stored in files, storage repositories, or on the web.	Plale	D2I	http://d2i.indiana.edu/xmccat	
Sigiri	2008	2011	Sigiri Job Scheduler provides a simple abstraction for interaction with heterogeneous resource managers spanning grid and cloud computing.	Plale	D2I	https://doi.org/10.1002/cpe.2823	*Withana, E.C. and Plale, B. (2012). Sigiri: uniform resource abstraction for grids and clouds. Concurrency & Computation: Practice and Experience, 24: 2362-2380. doi:*10.1002/cpe.2823

Fault Tolerant Hybrid Information Service (FTHPIS)	2011	2020	FTHPIS is a hybrid grid information service supporting both the scalability of large amounts of relatively slowly varying data and a high performance rapidly updated information service for dynamic regions.	G.C. Fox	DSC	http://www.opengrids.org/hybrid/index.html	
Twister	2010	2017	Twister is a software tool that supports faster execution of many data mining applications implemented as MapReduce programs.	Judy Qiu Fox	DSC	http://www.iterativemapreduce.org/	
Twister4Azure	2011	2013	Twister4Azure is an implementation of Twister for Azure environments.	Judy Qiu Fox	DSC	https://archive.codeplex.com/?p=twister4azure	
HARP	2016	Active	High Performance Machine Learning	Judy Qiu Fox	DSC	https://dsc-spidal.github.io/harp/	
Klatsch	2011	2011	An easy-to-program interface for exploring and analyzing feeds of social media data.	G.C. Fox	DSC	https://github.com/truthy/klatsch	
NaradaBrokering	2001	2009	A content distribution infrastructure that enables the development of secure, failure-resilient Systems.	G.C. Fox	DSC	http://grids.ucs.indiana.edu/ptliupages/projects/narada/	https://dl.acm.org/doi/10.5555/646439.693397
Carousel	2002	2008	Supports ubiquitous access computing systems from PDAs.	G.C. Fox	DSC	http://grids.ucs.indiana.edu/ptliupages/projects/carousel/software.htm	Sangmi Lee, Sunghoon Ko, Geoffrey Fox, Kangseok Kim, Sangyoon Oh A (2003) Web Service Approach to Universal Accessibility in Collaboration Services in Proceedings of 1st International Conference on Web Services Las Vegas June 2003
HPJava	2001	2007	HPJava is an environment for scientific and parallel programming using Java.	G.C. Fox	DSC	http://grids.ucs.indiana.edu/ptliupages/projects/HPJava/index.html http://www.hpjava.org/	Han-Ku Lee, Bryan Carpenter, Geoffrey Fox & Sang Boem Lim (2004) HP Java: Programming Support for High-Performance Grid-Enabled Applications, Journal of Parallel Algorithms and Applications, 19:2-3, 175-193, DOI: 10.1080/10637190410001725481

Global-MMCS	2001	2004	A collaboration system, which integrates various services including videoconference, instant messaging and streaming.	G.C. Fox	DSC	http://www.globalmmcs.org/	*http://grids.ucs.indiana.edu/ptliupages/publications/SC04_pstr_GlobalMMCS.pdf*
mpiJava	2001	2003	mpiJava is an object-oriented Java interface to the standard Message Passing Interface for parallel programming (MPI).	G.C. Fox	DSC	http://www.hpjava.org/mpiJava.html	
RaPyDLI	2018	Active	Rapid Python Deep Learning Infrastructure	G.C. Fox	DSC	https://www.dsc.soic.indiana.edu/current_projects	
Machine Learning for SPIDAL	2018	Active	Machine Learning tools as part of SPIDAL project	G.C. Fox	DSC	http://www.spidal.org/software.html	
MIDAS	2017	Active	Middleware for Data-Intensive Analytics and Science	G.C. Fox	DSC	https://www.dsc.soic.indiana.edu/current_projects	
Cloudmesh	2015	2018	Cloudmesh Client: an easy-to-use client for accessing hybrid and heterogeneous clouds	von Laszewski	DSC	https://github.com/cloudmesh/client	
CAFE	2006	Active	Computational analysis of (gene) family evolution	Hahn / Hensche l	NCGAS	http://www.indiana.edu/~hahnlab/software.html	Han, M.V., G.W.C. Thomas, J. Lugo-Martinez, and M.W. Hahn (2013) Estimating gene gain and loss rates in the presence of genome assembly and annotation error using CAFE 3. Molecular Biology and Evolution. 30:1987-1997 De Bie, T., Cristianini, N., Demuth, J. P., and Hahn, M. W. CAFE: a computational tool for the study of gene family evolution. Bioinformatics 22, (2006)
Heterogeneity test	2016	2018	Coalescent test for differences in allele frequency distributions	Lynch / Doak	NCGAS	http://www.indiana.edu/~hahnlab/software.html	Hahn, M.W., M.D. Rausher, and C.W. Cunningham (2002) Distinguishing between selection and population expansion in an experimental lineage of bacteriophage T7. Genetics. 161:11-20
Perlymorphism	2012	2016	A suite of population genetics tools for large DNA sequence datasets	Hahn / Hensche l	NCGAS	http://www.indiana.edu/~hahnlab/software.html	Stajich, J.E. and M.W. Hahn (2005) Disentangling the effects of demography and selection in human history. Molecular Biology and Evolution. 22:63-73
Trinity	2011	2014	RNA sequence assembly	Hensche l	NCGAS	http://trinityrnaseq.sourceforge.net	*Grabherr MG, Haas BJ, Yassour M, Levin JZ,*

						https://github.com/trinityrnaseq/trinityrnaseq/wiki	Thompson DA, Amit I, Adiconis X, Fan L, Raychowdhury R, Zeng Q, Chen Z, Mauceli E, Hacohen N, Gnirke A, Rhind N, di Palma F, Birren BW, Nusbaum C, Lindblad-Toh K, Friedman N, Regev A. Full-length transcriptome assembly from RNA-seq data without a reference genome. Nat Biotechnol. 2011 May 15;29(7):644-52. doi: 10.1038/nbt.1883. PubMed PMID: 21572440.
mlRho	2007	2010	Population mutation rates	Lynch / Doak	NCGAS	http://guanine.evolbio.mpg.de/mlRho/ http://www.ncbi.nlm.nih.gov/pubmed/20331786	HAUBOLD, B., PFAFFELHUBER, P. and LYNCH, M. (2010). mlRho – a program for estimating the population mutation and recombination rates from shotgun-sequenced diploid genomes. Molecular Ecology, 19: 277-284. doi:10.1111/j.1365-294X.2009.04482.x
XLiveCD	2003	2005	Open source system to allow Microsoft Windows users to access Linux X-term applications and graphics	Repasky	NCGAS	http://xlivecd.indiana.edu/	
CLSD Parser Scripts	2003	2006	Parser scripts supporting IBM DiscoveryLink	Stewart / Anderson	RT	https://sourceforge.net/projects/iuclsdparser/	
PHPCap	2017	Active	PHPCap is a PHP API (Application Programming Interface) for REDCap, that lets you: export, import, and delete data in REDCap	Meraz	RT	https://github.com/IUREDCap/phpcap	
redcap-etl	2017	Active	REDCap-ETL (REDCap Extract, Transform, Load) is an application that can extract data from REDCap, transform the extracted data, and load the transformed data into a database.	Meraz	RT	https://github.com/IUREDCap/redcap-etl	
redcap-etl external module	2018	Active	The REDCap-ETL (Extract Transform Load) external module extracts data from REDCap and transforms the extracted data			https://github.com/IUREDCap/redcap-etl-module	

			based on user-specified rules.				
SMBL (Simple Message Broker Library)	2003	2006	Tool for message passing interface programming with distributed systems	Stewart	RT	http://sourceforge.net/projects/smbl/	
PENELOPE-MPI	2002	2005	Parallel (supercomputer) software for studying radiation transport used in planning chemotherapy for brain cancer	Stewart	RT	Open source but not distributed in US without permission from government.	Stewart, C.A., D. Hart, R.W. Sheppard, H. Li, R. Cruise, V. Moskvin, L. Papiez. 2004. Parallel computing in biomedical research and the search for peta-scale biomedical applications. pp. 719-716 In: G.R. Joubert, W.E. Nagel, F.J. Peters, and W.V. Walter (eds). *Parallel computing: software technology, algorithms, architectures & applications.* Advances in Parallel Computing Vol. 13. Elsevier, Oxford. doi:10.1016/S0927-5452(04)80088-1
PINY_MD	2002	2004	Molecular dynamics simulation	Papakhian / Martyna	RT	https://sourceforge.net/projects/iupinymd/	
OpenXDMoD Value Analytics Module	2016	2019	Module for widely used OpenXDMod software that enabled reports linking usage of high performance clusters to success in obtaining grant funding for institutions of higher education	Link, Henschel	RT	https://open.xdmod.org/8.5/index.html	Ben Fulton, Steven Gallo, Matt Link, Robert Henschel, Tom Yearke, Katy Boerner, Robert L. DeLeon, Thomas Furlani, and Craig A. Stewart. 2017. Value Analytics: A Financial Module for the Open XDMoD Project. In Proceedings of Practice & Experience in Advanced Research Computing, New Orleans, Louisiana USA, July 2017 (PEARC17), 6 pages. DOI: 10.475/1234
Lustre UID/GID Mapping and Shared Key code	2009	2013	Contribution to Lustre base open source distribution allows secure use of Lustre file system over wide area networks	Simms	RT	http://opensfs.org/	*Henschel, R., S. Simms, M. Davy, D. Hancock, S. Michael, T. Johnson, N. Heald, T. William, M. Allen, R. Knepper, K. Seiffert, M.R. Link and C.A. Stewart. Demonstrating Lustre over a 100Gbps Wide Area Network of 3500km. In: Proceedings of SC'12. (Salt Lake City, UT, 2012)* https://dl.acm.org/doi/10.5555/2388996.2389005
Pubsonline	2003	2005	Online bibliographic management / presentation	Stewart	RT	https://sourceforge.net/projects/iupubsonline/	Myron, S.A., M.R. Link, R. Knepper, C.A. Stewart. 2005. PubsOnline: an open source database for managing and delivering bibliographic information.

							Proceedings of the 33rd annual ACM SIGUCCS conference on User services. 6-9 November 2005, Monterey, CA, USA. http://portal.acm.org/citation.cfm?id=1099492 DOI:https://doi.org/10.1145/1099435.1099492
High Performance Storage Systems (HPSS) connector for the Java framework	2001	2003	Contribution to HPSS base distribution to enable access via Java applets	Papakhian	RT	http://www.hpss-collaboration.org/	http://www.hpss-collaboration.org/documents/HPSSBrochure.pdf
Life Sciences DataBase Parsers	2001	2005	Software to input data into IBM DiscoveryLink	Stewart	RT / NCGAS	No longer available	
Catpa	2002	2004	Protein Analyzer	Stewart / Dalkilic	RT / NCGAS	No longer available	http://hdl.handle.net/2022/1830
GeneIndex	2008	2011	GeneIndex searches a genome for all words of length n or length n or less, and makes a full index	Stewart	RT / Office of the Executive Director	https://sourceforge.net/projects/iugeneindex/	Li, H., D. Hart, M. Mueller, U. Markwardt and C.A. Stewart. GeneIndex: An Open Source Parallel Program for Enumerating and Locating Words in a Genome. In: Proceedings of IJCBS '09. International Joint Conference on Bioinformatics, Systems Biology and Intelligent Computing (3-5 Aug. 2009). http://dx.doi.org/10.1109/IJCBS.2009.127
fastDNAml	1997	2003	Phylogenetic inference based on DNA sequences	Stewart	RT / Office of the Executive Director	https://sourceforge.net/projects/iupfastdnaml/ http://iubio.bio.indiana.edu/soft/molbio/evolve/fastdnaml/fastDNAml.html (broken link)	Stewart, C.A., D. Hart, D. K. Berry, G. J. Olsen, E. Wernert, W. Fischer. 2001. Parallel implementation and performance of fastDNAml - a program for maximum likelihood phylogenetic inference. Proceedings of SC2001, Denver, CO, November 2001. http://portal.acm.org/citation.cfm?id=582054 DOI:https://doi.org/10.1145/582034.582054
XCBC	2011	Active	XSEDE Compatible Basic Cluster	Stewart	RT / Office of the Executive Director	https://xcri-docs.readthedocs.io/en/latest/toolkits/xcbc-installation/	
XNIT	2011	Active	XSEDE National Integration Toolkit	Stewart	RT / Office of the Executive Director	https://xcri-docs.readthedocs.io/en/latest/toolkits/xnit-installation/	

Multi-user Tool Tracking (MUTT)			Software that tracks and decodes user interaction with physical objects used in a user interface. MUTT processes imagery captured by video camera.	Baker			
TOTAL TITLES	73						

Table A3.5-1. Open source software titles released by IU PTI.

13.6. Patents awarded to PTI-affiliated staff or faculty

US Patent Number	Year	Title	Inventors	Reference
8,775,495	2014	Compression system and method for accelerating sparse matrix computations	Andrew Lumsdaine, lead inventor	https://patents.google.com/patent/US8775495B2/en
8,817,015	2014	Methods, apparatus, and computer-readable storage media for depth-based rendering of focused plenoptic camera data	Andrew Lumsdaine, co-inventor	https://patents.google.com/patent/US8817015
8,860,833 B2	2014	Blended rendering of focused plenoptic camera data	Andrew Lumsdaine, co-inventor	https://patentimages.storage.googleapis.com/5b/d2/01/3b805c9644379f/US8860833.pdf
8,345,144	2013	Methods and apparatus for rich image capture with focused plenoptic cameras	Andrew Lumsdaine, co-inventor	https://www.lens.org/lens/patent/US_8345144_B1
8,379,105	2013	Methods and apparatus for full-resolution light-field capture and rendering	Andrew Lumsdaine, co-inventor	https://patents.google.com/patent/US8379105
8,400,555	2013	Focused plenoptic camera employing microlenses with different focal lengths	Andrew Lumsdaine, co-inventor	https://patents.google.com/patent/US8400555B1/en
8,189,065B2	2012	Methods and apparatus for full-resolution light-field capture and rendering	Andrew Lumsdaine, co-inventor	https://patentswarm.com/patents/US10390005B2
8,189,089	2012	Methods and apparatus for reducing plenoptic camera artifacts	Andrew Lumsdaine, co-inventor	https://patents.google.com/patent/US8189089B1/en
8,724,000	2012	Methods and apparatus for super-resolution in integral photography	Andrew Lumsdaine, co-inventor	https://patentimages.storage.googleapis.com/bf/30/f1/9377b4270d08aa/US8724000.pdf
7,962,033	2011	Methods and apparatus for full-resolution light-field capture and rendering	Andrew Lumsdaine, co-inventor	https://patents.google.com/patent/US7962033B2/en
20090054106A1	2009	Radiotelephone equipment detail base station detail having specific antenna arrangement	Danko Antolovic, Steven S. Wallace	https://patents.google.com/patent/US20090054106A1/en
6,078,948	2000	Platform-independent collaboration backbone and framework for forming virtual communities having virtual rooms with collaborative sessions	Geoffrey C. Fox was a co-inventor	https://patents.justia.com/patent/6078948
Patents total	**12**			

Table 6-1. Patents issues to PTI-affiliated faculty or staff

13.7. Commercial licenses executed

Name	Executed	Description	Relationship to PTI	Website

Boost software (boost.iu.edu)	2019	This software was being licensed as the eLearning lab was being created.	Developed by eLearning Lab Director Ben Motz and colleagues, boost is a mobile app that serves as "a personal assistant for online learning"	boost.iu.edu
Augmented reality device	2017	PIPES augmented reality design licenses for commercialization to startup founded by inventor, who was an IU staff member	Augmented reality system invented by RT/AVL staff member Chauncey Freund	
Facial recognition software	2016	Licensed for use by local law enforcement agencies	Invented by CREST staff member Matthew Anderson	
Novel HPC processor design	2016	Licensed for use by startup led by Professor Sterling	Invented by PTI-affiliated faculty member Thomas Sterling	
John - e - Box 1M cube stereoscopic display device	2003	Licensed to manufacturing firm in 2004; production ended as a result of viability of high resolution flat panel TV screens	Invented by John N. Huffman and Eric Wernert, staff with Research Technologies Division of UITS, along with John C. Huffman	
Total licenses	**5**			

Table A3.7-1. Commercial licenses executed by PTI and PTI-affiliated groups or inventors.

13.9. Startup companies created by someone affiliated with PTI

Name	Started	Status	Relationship to PTI	Website
Startups created by PTI-affiliated staff (all located in Indiana)				
CloudSeal	2018	Purchased by Facebook	Founded by Prof. Ryan Newton, one of the Associate Directors of CREST, now a group leader for Facebook	cloudseal.io
Simultac LLC	2018	Active	Startup founded by Luddy Professor (and former director of Center for Research in Extreme Scale Technologies) Thomas Sterling	http://www.simultac.com
CyUtil	2017	Active	Augmented reality startup founded by Research Technologies staff member Chauncey Freund	http://www.cyutil.io
Chalklabs	2008	Active	Started by two former students of Katy Boerner, who was a PTI fellow	https://chalklabs.com
White River Labs, LLC	2007	Defunct as of 2009	LLC created by Lab Director Andrew Lumsdaine and former Ph.D. student Christopher Mueller	
Precise Path Robotics (initially IndyRobotics LLC)	2006	Highly successful, bought out by MTD Products, Inc.	Precise Path Robotics developed (using patented technology) autonomous, self-driving lawnmowers. This company was an offshoot of an LLC created with assistance from what is now CACR to participate in the DARPA autonomous vehicle challenge held in 2004	https://www.mtdproducts.com/equipment/mtdproducts
Acquired S Science LLC	2004	Defunct as of 2008	LLC created by leadership of Scientific Data Analysis Lab	
Anabas	2003	IU ended interest in company in 2008, local (Bloomington) office closed.	Geoffrey C. Fox was a co-founder. PTL Capital Investment Fund made initial investments in startup.	http://www.anabas.com
EnVizable LLC	2003	Defunct as of 2008	LLC started by sab Director Pauline Baker. PTL Capital Investment Fund made initial angel investment.	
SGC Technologies	2003	Defunct as of 2007	LLC started by staff of Advanced Network Management Lab; PTL Capital Investment Fund made initial angel investment.	
Veterisoft, Inc	2003	Defunct as of 2007	Startup created by Lab Director Andrew Lumsdaine	
Total startups created by PTL / PTI Staff	**11**			

Table 8-1. Startup companies created by PTI or PTI-affiliated researchers.

13.10. Startup companies in which PTL and PTI made an investment as an Angel Investor

Startups in which IU made an investment through the PTL Capital Investment Fund (all firms located in Indiana)				
Haelen Group	2001- 2007 (now defunct)	Purchased by Careguide	PTL Capital Investment Fund was angel investor	
Chartlogix / Dynomed	2001 - 2007	Defunct	PTL Capital Investment Fund was angel investor	
Total other startups receiving investments from PTL Capital Investment Fund				

Table A3.9-1. Companies in which PTI made an investment acting as an "angel investor." All investments were in companies operating within the State of Indiana.

13.11. Collaborations with/support for business in (or with offices in) Indiana

Company	Start	End	Relationship to PTI	Website
SproutBox	2018-	Active	Leaders affiliated with PTI have made personal investments to support the efforts of the top venture capital firm in Bloomington, IN	sproutbox.com
Rofori	2018	2019	CACR worked with Rofori to provide an assessment and feedback on their product when they first moved to Indiana.	https://rofori.com/
Rolls Royce, Inc.	2016	Active	Collaboration as part of the Virtual Validation, Verification, and Visualization Institute - a private - public partnership for advancing the state of the art in digitally-enabled engineering and manufacturing processes	v4i.us
Cummins, Inc.	2008 -- 2018	On hold, till arrival of Big Red 200 supercomputer	Research Technologies collaborated with Cummins to improve Cummins workflow for simulations used by Cummins in designing diesel piston heads	https://www.cummins.com
Masterbrand Cabinets, Inc	2016- 2018	Ended (with successful conclusion of project)	The Advanced Visualization Lab of UITS was contracted by Masterbrand Cabinets to consult on workflows and best practices for managing the production, reuse, and storage of 3D digital assets for its diverse line of cabinetry products, with uses spanning design, manufacturing, printed materials, Web sites, and VR marketing at retailers.	https://www.masterbrand.com/
Cigital, subsequently bought out by Synopsis	2015	Local office still active, after Cigital buyout by Synopsis	Cigital set up a "back office" location in Bloomington for cybersecurity operations, because of relationship between Cigital CIO and PTL Science Director Dennis Gannon, and because of availability of students available for hire locally	https://www.bloomingtontech.com/cigital-expanding-bloomington-office/
John Andretti Racing	2009	Ended	Short term consultation on potential role of CFD simulations in IndyCar design, joint with Purdue University	
IBM, Inc.	2007-2009	Ended when IBM discontinued efforts on Cell processor	PTI provided space for an IBM programming team working on porting applications to the Cell processor.	
Wisdom Tools	1999	Acquired by another company, closed down in 2015	Wisdom Tools offices were set up in PTL space in the former PTL headquarters in the Showers Building. PTL and Wisdom Tools staff collaborated.	
Collaborations with /support for business in Indiana				**9**
Collaborations with /support for national and international business				

IBM	1996-2006	Ended	Extended R&D collaborations related to supercomputer	
Penguin Computing	2011-2013	Ended	PTI hosted a cluster owned and operated by Penguin computing, with PTI responsible for installing bioinformatics software on the cluster and supporting users of that system, as an experiment in early applications of cloud computing for bioinformatics	
Microsoft, Inc.	2005, 2018-present	One engagement finished, one ongoing	Two engagements with Microsoft: a $25,000 gift to support performance analysis of MS HPCServer in 2005, and a $1M contract for 2019- to fund the "Humans Accelerating Research in the Cloud" project	
Collaborations with /support for national and international business				3
Total major collaborations with private companies	**11**			

Table A3.10-1. Companies with which PTI has had extensive collaborations. All companies are either based in Indiana or have major operations within the State.

13.12. Individuals receiving a Ph.D. via work with IU PTI

Name	Center or Lab	If Ph.D. Awardee went on to a tenure-track position, what institution?
Christopher Soghoian	CACR	
Joseph Cottam	CREST	
Bryan Barrett	CREST / Open Systems Lab	
Joshua Hersey	CREST / Open Systems Lab	
Lie-Quan Lee	CREST / Open Systems Lab	
Prabhanjan Kambadur	CREST / Open Systems Lab	
Torsten Hoeffler	CREST / Open Systems Lab	ETH Zürich
Thejaka Amila Kanewala	Cyberinfrastructure Integration Research Center	
Chathura Kamalanath Herath	Data to Insight Center	
Devarshi Ghoshal	Data to Insight Center	
Eran Chinthaka Withana	Data to Insight Center	
Guangchen Ruan	Data to Insight Center	
Isuru Suriarachchi	Data to Insight Center	
Jiaan Zeng	Data to Insight Center	
Lavanya Ramakrishnan	Data to Insight Center	
Milinda Pathirage	Data to Insight Center	
Nithya Nirmal Vijayakumar	Data to Insight Center	
Peng Chen	Data to Insight Center	
Scott Jensen	Data to Insight Center	San Jose State University
Srinath Perera	Data to Insight Center	
Stacy Kowalczyk	Data to Insight Center	Dominican University
Ying Liu	Data to Insight Center	
Yogesh Simmhan	Data to Insight Center	Indian Institute of Science
You-Wei Cheah	Data to Insight Center	
Yuan Luo	Data to Insight Center	
Zong Peng	Data to Insight Center	
Ahmet Ercan Topçu	Digital Science Center	American University of the Middle East
Ahmet Fatih Mustacoglu	Digital Science Center	
Ahmet Sayar	Digital Science Center	Kocaeli University
Ahmet Uyar	Digital Science Center	Melikşah Üniversitesi
Ali Kaplan	Digital Science Center	
Andrew J. Younge	Digital Science Center	

Beytullah Yildiz	Digital Science Center	Atilim University
Bingjing Zhang	Digital Science Center	
Choonhan Youn	Digital Science Center	
Galip Aydin	Digital Science Center	Firat University
Han-Ku Lee	Digital Science Center	Konkuk University
Harshawardhan Gadgil	Digital Science Center	
Hasan Bulut	Digital Science Center	Ege University
Hyungro Lee	Digital Science Center	
Jerome Mitchell	Digital Science Center	
Jong Youl Choi	Digital Science Center	
Jungkee Kim	Digital Science Center	Sungkonghoe University
Kangseok Kim	Digital Science Center	
Mehmet Aktas	Digital Science Center	Yildiz Technical University
Mehmet Nacar	Digital Science Center	Harran University
Minjun Wang	Digital Science Center	
Saliya Ekanayake	Digital Science Center	
Sang Boem Lim	Digital Science Center	Konkuk University
Sangmi (Lee) Pallickara	Digital Science Center	Colorado State University
Sangyoon Oh	Digital Science Center	Ajou University
Seung-Hee Bae	Digital Science Center	Western Michigan University
Supun Kamburugamuve	Digital Science Center	
Tao Huang	Digital Science Center	
Thilina Gunarathne	Digital Science Center	
Xiaohong Qiu	Digital Science Center	Indiana University
Xiaoming Gao	Digital Science Center	
Yang Ruan	Digital Science Center	
Zhenhua(Gerald) Guo	Digital Science Center	
Akarsu Erol	Digital Science Center / Community Grids Lab	
Dincer Kivanc	Digital Science Center / Community Grids Lab	University of Washington
Gurhan Gunduz	Digital Science Center / Community Grids Lab	Mugla Sitki Kocman University
Mehmet Sen	Digital Science Center / Community Grids Lab	
Alaa Abi-Haidar	Digital Science Center / Complex Networks and Systems Lab	
Ben Markines	Digital Science Center / Complex Networks and Systems Lab	
Jacob Ratkiewicz	Digital Science Center / Complex Networks and Systems Lab	

Marcio Mourao	Digital Science Center / Complex Networks and Systems Lab	
Mark Meiss	Digital Science Center / Complex Networks and Systems Lab	
Matthew Whitehead	Digital Science Center / Complex Networks and Systems Lab	
Michael A. Evans	KapLab	Virginia Tech University
Mira Han	NCGAS	University of Nevada-Las Vegas
Richard Knepper	Research Technologies	
Scott Michael	Research Technologies	
Total	**73**	

13.13. Distinguished and chaired professorships, lifetime achievement awards, other major awards

There are certain categories of achievement and awards that are particularly special and notable: distinguished professorships, chaired (named) professorships, lifetime achievement awards given by major professional organizations, and awards at international conferences. IU PTI and affiliated faculty and staff have received many such awards and accolades.

Years	Name	Honor Type	Scope	Organization	Details
2020	Beth Plale	Named (chaired) professorship	Local	IU	Dr. Beth Plale, founding director of the Data to Insight Center, was in 2020 named the inaugural Michael A. McRobbie and Laurie Burns McRobbie Bicentennial Professorship in Computer Engineering
2019	Geoffrey C. Fox	Lifetime Achievement Award	National	HPDC(High Performance Distributed Computing Conference)	HPDC Achievement Award for Foundational contributions to parallel computing, high-performance software, the interface between applications and systems, contributions to education, and outreach to underrepresented communities
2019	Geoffrey C. Fox	Lifetime Achievement Award	National	ACM-IEEE	Ken Kennedy Award for Foundational contributions to parallel computing methodology, algorithms and software, data analysis, and their interface with broad classes of applications
2014	Thomas Sterling	National Academy Membership	National	AAAS	Fellow
2013	Katy Boerner	Distinguished Professorship and Named (chaired) professorship	Local	IU	Dr. Katy Boerner was named the Victor H. Yngve Professor of Engineering & Information Science and subsequently the second person ever promoted to the rank of Distinguished Professor within the School of Informatics, Computing, and Engineering. Early in her career at IU Dr. Boerner was provided research funding support as a Pervasive Technology Labs Fellow.
2013	Suresh Marru	Foundation Fellow	International	Apache Software Foundation	Elected as an Apache Foundation Fellow in 2013
2013	Marlon Pierce	Foundation Fellow	International	Apache Software Foundation	Elected as an Apache Foundation Fellow in 2013
2013	Thomas Sterling	Lifetime Achievement Award	International	IEEE/ACM SCxy Conference	HPC Vanguard Award
2011	Geoffrey C. Fox	Distinguished Professorship	Local	IU	Dr. Geoffrey C. Fox, Founding Director of the Digital Science Center, was the first person ever promoted to the rank of Distinguished Professor within the School of Informatics, Computing, and Engineering.
2011	Geoffrey C. Fox	National Academy Membership	National	ACM	Fellow

2011	Craig Stewart	NSF Advisory Committee for Cyberinfrastructure membership	National	NSF	Stewart led this task force to define a whole new area of cyberinfrastructure leading to new solicitations from the NSF and new funding to IU to lead campus bridging efforts within XSEDE.
2007	Stephen Simms	International competition award: SC07 Bandwidth Challenge	International	IEEE/ACM Supercomputing Conference	Simms led an international team executing a project called "Using the Data Capacitor for Remote Data Collection, Analysis, and Visualization." This team won the highly competitive SC07 Bandwidth Challenge (http://hdl.handle.net/2022/14615)
2006	Simms, S.C.; M. Davy, C. Hammond, M.R. Link, S. Teige, M-H Baik, Y. Manri, R. Lord, D.F. McMullen, J.C. Huffman, K. Huffman, G. Juckeland, M. Kluge, R. Henschel, H. Brunst, A. Knuepfer, M. Mueller, P.R. Mukund, A. Elble, A. Pasupuleti, R. Bohn, S. Das, J. Stefano, G.G. Pike, D. Balog, C.A. Stewart	International competition runner up: SC06 Bandwidth Challenge	International	IEEE/ACM Supercomputing Conference	Simms and Plale led an international team executing a project called "All in a Day's Work" using the IU Data Capacitor. This team was the runner up in the highly competitive SC06 Bandwidth Challenge https://itnews.iu.edu/articles/2006/all-in-a-days-work-indiana-university-team-receives-award-in-supercomputing-conference-bandwidth-challenge.php
2006	Craig Stewart	Fellowship	International	Fulbright Foundation	Stewart was a Fulbright Senior Specialist visiting Technische Universität Dresden in 2006 https://honorsandawards.iu.edu/research-creative/fulbright.shtml
2003	Craig Stewart	International competition award: SC03 HPC Challenge	International	IEEE/ACM Supercomputing Conference	Stewart led an international team that created a computing grid spanning every continent other than Antarctica to perform groundbreaking research on arthropod evolution. http://portal.acm.org/citation.cfm?id=1033261
1997*	Randall Bramley Craig Stewart	International competition award: SC97 HPC Challenge	International	IEEE/ACM Supercomputing Conference	IU Computer Science Professor Randall Bramley (with assistance of Stewart and other staff who would becomeIU PTI staff) won the SC97 HPC Challenge for High Performance Applications with an international grid performing simulations of mold filling by molten metal and subsequent solidification of engineered objects.
1990*	Geoffrey C. Fox	National Academy Membership	National	American Physical Society (APS)	Fellow
*Technically, these awards pre-date IU PTI, but we're still pretty chuffed about them. Not many people are named Fellows to multiple international scientific communities, and very few universities have won as many as three total challenge awards at the IEEE/ACM Supercomputing Conference.					

13.14. International, national, state, and university leadership, and regional and state awards

Through IU PTI, Indiana University influences local, state, and national high-technology ecosystems. This is a critical part of IU's engagement in the US and the world: providing insights about research and research infrastructure priorities as they exist now, and regarding what they should be in the future. Leadership in conferences, workshops, and work with state and federal agencies represent critical contributions to our society as well as to the collective knowledge possessed by humanity.

Years	Name	Honor Type	Scope	Organization	Details
2020	Von Welch	Government Service	State	State of Indiana	CACR Director Von Welch is leading an effort funded by the state of Indiana to prepare election officials in all 92 Indiana counties for cybersecurity incidents in preparation for the 2020 general election and beyond.
2019 - present (2020)	Martin Swany	Leadership	Local	IU	Dr. Martin Swany, faculty affiliate of the D2I Center, is currently the chairperson of the Department of Intelligent Systems Engineering in Luddy SICE.
2019	Fred Cate	Testimony	National	US Congress	Fred H. Cate has testified before numerous congressional committees and speaks frequently before professional, industry and governmental groups. Most recently he testified at an FTC "Approach to Consumer Privacy" hearing on April 9 2019.
2018 - present (2020)	David Y. Hancock	Advisory Board Member	National	XSEDE	Elected member of the XSEDE Advisory Board representing the Service Provider Forum since 2018 to the present.
2018 - present (2020)	Junjie Li	Leadership	International	SPEC HPG (http://spec.org/hpg/)	SPEC HPG Secretary from 2018–present
2018 - present (2020)	Von Welch	Major Government Agreement	National	DoD	CRADA representing a follow on and expansion of the prior CRADA between NWSC Crane and IU
2017 - present (2020)	Robert Henschel	Leadership	International	SPEC HPG (http://spec.org/hpg/)	SPEC HPG Chair from 2017 to present
2017 - present (2020)	Scott Michael	Leadership	International	Cray User Group (CUG)	Treasurer of CUG since 2017
2017 - present (2020)	Beth Plale	National Government Service	National	NSF	Science Advisor for Public Access (IPA) and a program officer in the CISE directorate
2017 - 2020	Kenrick Rawlings	Leadership	National	OpenSFS / Lustre Users Group (http://opensfs.org/)	Secretary, Board of Directors of OpenSFS
2016 - 2018	Craig Stewart	Advisory Board Member	National	XSEDE	Service Provider representatives to the XSEDE Advisory Board from 2016-2018
2016 - present (2020)	Stephen Simms	Leadership	National	OpenSFS / Lustre Users Group (http://opensfs.org/)	Founding member and community representative on the Board of Directors for OpenSFS, a critical organization in Lustre Development and organizer of the annual Lustre User Group conference. OpenSFS President 2016-2017, 2019-present. From his role as community board member he went on to have an important role in transforming the organization to a user driven model.
2016 - 2018	Von Welch	Major Government Agreement	National	DoD	CACR was responsible for the execution of the first CRADA between IU and Crane Naval Weapons Support Center (NWSC) in the last 20 years. This CRADA is the foundation of IU's relationship with Crane NWSC
2016	Geoffrey Fox	Leadership	Local	IU	Dr. Geoffrey C. Fox was the founding chairperson of the Department of Intelligent Systems Engineering in Luddy SICE.

2015 - present (2020)	Von Welch	Center of Excellence Designation	National	NSA/DHS	IU designation as NSA/DHS National Center of Academic Excellence renewed: National Security Agency and the Department of Homeland Security renewed its designation of Indiana University as a National Center of Academic Excellence in Cyber Defense Research (CAE-R) and as a National Center of Academic Excellence in Information Assurance Education (CAE-E) through 2021.
2015 - present (2020)	Von Welch	Advisory Board Member	National	InCommon	Appointed to the InCommon Steering Committee as an advisor representing the research community, a newly created position recognizing Welch's leadership
2015 - 2016	Craig Stewart	Government Service	National	NSF	Part time appointment at the NSF BIO directorate as an Expert
2013	Stephanie Cox, Robert Henschel				IUanyWare received a Technology in Education Excellence & Innovation Award at the 2013 TechPoint Mira Awards. http://blog.techpoint.org/blog/indiana-technology-news-2/iuanyware-wins-technology-in-education-post-secondary-excellence-and-innovation-award
2012 - 2014	David Y. Hancock	Leadership	National	XSEDE	Inaugural vice chair of the XSEDE Service Providers Forum
2012 - 2014	Craig Stewart	Advisory Board Member	National	InCommon	InCommon Steering Committee
2010 - present (2020)	David Y. Hancock	Leadership	International	Cray User Group (CUG)	Member of the board of directors since 2010: 2010-2014 Vice President and Program Chair; 2014-2018 President; 2018- director at large
2009 - 2015	David Y. Hancock	Leadership	International	HPCXXL / SPXXL	Vice President of the SPXXL users' group (the IBM HPC user group) from 2009-2015, helped transition the group to HPCXXL, now a multi-vendor user group and recognized non-profit corporation.
2008 - 2011	Geoffrey C. Fox	Advisory Board Member	National	NSF	Geoffrey C. Fox was a member of NSF Advisory Committee for Cyberinfrastructure from 2008 to 2011 and during this time was Co-Chair of the NSF ACCI Taskforce on Cyberlearning and Workforce Development (CLWD) Task Force Leadership.
2008 - 2011	Craig A. Stewart	Advisory Board Member	National	NSF	Member of the NSF Advisory Committee for Cyberinfrastructure from 2008 to 2011 and during this time was Chair, NSF Advisory Committee for Cyberinfrastructure Task Force on Campus Bridging
2007	Craig A. Stewart	Testimony before Congressional Committee	National	US Congress	Craig Stewart testified before the House Science and Technology Committee regarding the 2007 report of the President's Council of Advisors on Science and Technology. http://hdl.handle.net/2022/5124
2006 - 2008, 2019 - 2020	Craig A. Stewart	National organization leadership	National	CASC (Coalition for Advanced Scientific Computation)	Chair, 2006-2008, Secretary 2019-2020
2005	PTL	Mira Award	Statewide	TechPoint, and Indiana high-tech collective	Innovative tech organization runner up
2003 - 2019	Matthew Link	International organization leadership	International	SCxy Conference	Matthew Link has held a number of leadership positions within the organizational structure of the annual international IEEE/ACM SCxy conference, including being elected to serve on the SCxy steering committee - the top level organizing body of this conference. Link is the only member of the IU community to serve at this level of the SCxy organizational structure.
	Rob Quick	Leadership	International	*Committee on Data (CODATA) of the International Science Council (ISC)*	Rob Quick is a co-director.

2007	Kurt Seiffert	Leadership	International	*HPSS User Forum Conference Chair*	IU Hosted the 2007 HPSS User Forum (HUF).
2011	Kristy Kallback-Rose	Leadership	International	*HPSS User Forum Conference Chair*	IU Hosted the 2011 HPSS User Forum (HUF).
2019	Charlie McClary	Leadership	International	*HPSS User Forum Conference Chair*	IU Hosted the 2019 HPSS User Forum (HUF).
2019-202	Bill Sherman	Leadership	National	*THE CAAV - The Higher Education Campus Alliance for Advanced Visualization*	*Executive committee founding member. He is coordinating the CAAV 2019 Conference in Bloomington Oct 15-17*
2014–2019	John Walsh	Editor-in-Chief	International	*Journal of the Text Encoding Initiative*	
Present	John Walsh	Technical Editor	International	*Digital Humanities Quarterly*	*The Digital Humanities Quarterly is an open-access, peer-reviewed, digital journal covering all aspects of digital media in the humanities. Published by the Association for Computers and the Humanities (ACH) and the Alliance of Digital Humanities Organizations (ADHO).*
2018	David Hancock, Craig Stewart, and the Jetstream Team	Award	National	*Campus Technology Impact Award in IT Infrastructure and Systems*	*https://campustechnology.com/articles/2018/12/13/putting-advanced-computing-power-within-reach.aspx*

13.15. Financial Support

Over the last 20+ years, PTI has received financial support from the following federal and state agencies, private charitable foundations, and private companies.

- Air Force Office of Scientific Research (AFOSR)
- Alfred P. Sloan Foundation
- The Andrew W. Mellon Foundation
- Cray
- Defense Advanced Research Projects Agency
- Dell
- Department of Energy Office of Science
- Department of Homeland Security
- HP/HPE
- IBM
- Institute of Museum and Library Services
- Intelligence Advanced Research Projects Activity (IARPA)
- Lilly Endowment Inc.
- Microsoft
- National Aeronautics and Space Administration (NASA)
- National Endowment for the Humanities (NEH)
- National Institute of Standards and Technology (NIST)
- National Institutes of Health
- National Security Agency (NSA)
- National Science Foundation
- State of Indiana
- Sun Microsystems

14. Appendix 5: Comparison of IU PTI with similar organizations nationally

IU PTI is a peerless organization, perhaps less in the usual sense than due to its unique organizational structure. The table below presents information about a variety of other cyberinfrastructure organizations operating at the national or regional level.

Table A3-1: Comparison of Major Supercomputing Centers, as of July 1 2020, organized by number of FTEs

Center	Staff	Compute (PFLOPS)	Disk (PB)	Tape (PB)
ISI	331	-	-	-
NCSA	241	1.6	28	500
SDSC	230	3.1	15.3	-
TACC	159	19+	39	160
Argonne National Labs	123	21.7	43.5	65
IU PTI	**107**	**7.1**	**9.25**	**58**
PSC	60	1.7	16	-
Purdue Research Computing (within IT@P)	56	0.9	9.1	10
Minnesota Supercomputing Center	46	0.9	4.9	-
Ohio Supercomputing Center	28	1.8	5	5.5
NICS	22	0.2	1.7	-
Notre Dame	19	< 1.0	3	-
Cornell Center for Advanced Computing	18	-	-	-
University of Chicago exclusive of ANL	17	< 1.0	3.7	-

The information in Table A3-1 was compiled from public sources (with the exception of IU PTI) and may differ from internal accounting of staff and inventory at each center. Where performance data was not publicly available, it was estimated from the available information (e.g., nodes, cores, and CPU family). In some instances, no public information was available (empty entries). The information for IU PTI includes RT.

Observations about similar organizations at other institutions include the following:

- The USC Information Sciences Institute (ISI) is similar to but larger than the aggregate portions of IU PTI that focus on software creation and deployment. ISI is structured very differently than IU PTI. It is much larger, and has 12 individuals in its executive leadership team. It also has a F&A rate that has 65% as its floor, and goes up from there depending on the size of grant budgets. ISI and IU PTI differ in that ISI operates no cyberinfrastructure facilities itself.
- The National Center for Supercomputing Applications (NCSA) still has the largest dedicated full time staff of any of the "NSF-centric" advanced cyberinfrastructure facilities, fitting to its history and prominence in the past.
- The Texas Advanced Computing Center (TACC) became involved in TeraGrid the same year as IU. They have grown faster than IU PTI partly due to highly significant subsidies from the state of Texas and the University of Texas at Austin, and partly because a specific part of their mission has been to become one of the national CI facility leaders.
- Argonne National Labs has a very specialized mission, and a combination of DOE, DOD, and NSF funding.
- The Pittsburgh Supercomputing Center is similar to NCSA and TACC in having been one of the original five NSF-funded supercomputer centers. (Few remember the 5th of the five because the NSF award supporting it ended after just one year: it was the John von Neumann Center at Stanford University).

Setting aside ISI, if one wanted to group the centers that run CI facilities and do software development and data management under NSF funding, one might cluster them out as follows:

- NCSA and TACC as the two clear national leaders among centers running primarily on NSF funds
- Argonne National Labs as a large center in terms of processing capacity, and unusual center because of its unique mix of DOE and NSF funds
- SDSC, PSC, and IU PTI all grouped together in the next tier
- Several other smaller centers clearly well behind IU PTI and PSC

Some supercomputer /cyberinfrastructure centers that were larger than IU PTI in 1999, but which IU PTI is now larger, and more productive, than include the Cornell Theory Center/Center for Advanced Computing (one of the other five NSF supercomputing centers), the Ohio Supercomputing Center, the Minnesota Supercomputing Center, the Arctic Region Supercomputing Center, and the Wright Patterson AFB DOD HPC Center.

While IU PTI is, indeed, without a precise peer, several smaller centers are using IU PTI as an example as they work to develop their own cyberinfrastructure centers. For instance, the Rutgers Discovery Informatics Institute (RDI2 - https://rdi2.rutgers.edu), the Ken Kennedy Institute for Information Technology (Rice University), and the IT center of the University of Wyoming are among several organizations being developed in line with IU PTI's example.

15. Appendix 6: Leaders of the Pervasive Technology Institute, Past and Present

PTI and PTL Senior Leadership
Principal Investigator for Lilly Endowment grant awards that established the Pervasive Technology Labs and the Pervasive Technology Institute: Michael A. McRobbie
Executive Director: Craig Stewart
Science Director: Beth Plale
Chief Scientist (PTL): Dennis Gannon
Chief Operating Officer (PTL): Brian D. Voss, Craig Stewart

ANML – Advanced Network Management Lab
Director: Steven S. Wallace

CACR - Center for Applied Cybersecurity Research
Directors: Fred Cate, Von Welch
Administrative Directors: Leslee Bohland, Dara Eckert
Associate Directors: Mark Bruhn, Bill Barnett, Scott Or
Senior Managers: Management: Craig Jackson, Mark Krenz, Anurag Shankar, Kelli Shute, Susan Sons
Associated Faculty: L. Jean Camp, Damir Cavar, Rachel Dockery, Arjan Durresi, David P. Fidler, Raquel Hill, Apu Kapidia, Steven Myers, Scott Schakelford, Joseph Tomain, XiaoFeng Wang, Xukai Zou

CIRC – Cyberinfrastructure Integration Research Center
Director: Marlon Pierce
Associate Director: Suresh Marru

> **Crisis Technologies Innovation Lab**
> Lab Co-Directors: David Wild, Robert Henschel, Matthew R. Link

CREST – Center for Research in Extreme Scale Technologies
Directors: Andrew Lumsdaine, Thomas Sterling
Deputy Directors: CD. Martin Swany, Craig Stewart
Associated Faculty Members: Ryan Newton, Jeremy Siek, D. Martin Swany

D2I – Data to Insight Center
Director: Beth Plale
Deputy Director: Robert McDonald
Associated Faculty: Inna Kouper, Xiaozhong Liu, Dennis Gannon, David Leake, Robert McDonald, . D. Martin Swany.
D2I fellows: Margaret Dolinsky (cofunded with Institute for Digital Arts and Humanities), Sandra Kubler (cofunded with Institute for Digital Arts and Humanities), Geoffrey Brown, David Crandall, David Leake, Fillipo Menczer, Arndt Schimmelmann

> **eLearning Research and Practice Lab**
> Lab Director: Benjamin Motz
> Lab associated faculty: Anastacia Morrone

DSC – Digital Science Center
Director: Geoffrey C. Fox
Assistant Directors: Judy Qiu Fox, Gregor von Laszewski

Associated Faculty: David Crandall, Judy Qiu Fox, Gregor von Laszewski, Andrew Lumsdaine, Filippo Menzer, Bo Peng

KAPLab – Knowledge Analysis and Projection Lab
Director: D.F. "Rick" McMullen

NCGAS – National Center for Genome Analysis Support
Managers: Richard Repasky, William K. Barnett, Thomas Doak, Richard LeDuc, Sheri Sanders
Associated Faculty: Scott Michaels, Matthew W. Hahn, Michael Lynch, Geoffrey C. Fox, Yuzhen Ye

RT – Research Technologies
Associate Dean / Associate Vice Presidents: Christopher S. Peebles, Bradley C, Wheeler, Craig A. Stewart, Matthew R. Link
Directors: William K. Barnett, Tom Hacker, David Y. Hancock, Robert Henschel, Therese Miller, D. Scott McCaulay, Matthew R. Link, Eric Wernert

SDAL – Scientific Data Analysis Lab
Director: Randy Heiland

VIS – Visualization and Interactive Spaces Lab
Director: Pauline Baker